

**Dinoflagellate cysts across the Cretaceous–Paleogene (K/Pg) boundary in the North Pacific;
biostratigraphy, diversity, and paleoenvironmental reconstructions**

by

Sandy Melvin Stuart McLachlan
B.A., University of Victoria, 2010
M.Sc., University of Victoria, 2017

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Abstract

The central objective of this study is to understand phytoplankton community response following the global mass extinction event at the Cretaceous–Paleogene (K/Pg) boundary. The objective is approached through analysis of dinoflagellate cyst assemblages across the boundary interval in the North Pacific. Dinoflagellate cysts are powerful tools for deep time paleoenvironmental reconstructions and this group of microfossils has been vastly underutilized in this region of the world. On this premise, comprehensive marine palynological surveys were undertaken for the Oyster Bay Formation of eastern Vancouver Island, British Columbia, Canada and Shatsky Rise in the northwest Pacific. The Oyster Bay Formation work resulted in the discovery of the first K/Pg boundary succession west of the Rocky Mountains based on biostratigraphic controls and refined taxonomy for the genus *Cannosphaeropsis* found within these strata. Three new taxa are described: *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov., *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov. and *Phelodinium fensomei* sp. nov. The cyst assemblages reveal endemic associations and signals of transition between offshore coastal to estuarine settings in keeping with global eustatic trends. Oyster Bay Formation results and interpretations are compared to analyses of core samples from Deep Sea Drilling Project Site 577 at Shatsky Rise. Contrast is seen between a diverse, highly productive coastal to estuarine environment in the Oyster Bay Formation as represented by organic-walled taxa and an oligotrophic bathyal environment at Shatsky Rise during the same interval as represented by a small number of calcareous taxa. These two regions form the basis for comparison between differing assemblages in order to ascertain the extent to which phytoplankton communities were affected by changes in sea-surface and water mass conditions in conjunction with the K/Pg event. The findings reveal measurable impacts of climate and paleoenvironmental change reflected by shifts in assemblage composition and cyst morphology. A lack of extinction among many forms is consistent with studies from around the globe as presented in an exhaustive review of the literature. The dinoflagellates were marginally impacted with the most specialized taxa presenting a record of sea-surface temperature fluctuation, nutrient supply and opportunistic niche exploitation.

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network in focus. 7, plesiotype, AW 1.3 m, Sample 58 (UVic 18-181, slide C, EF: W43/3), left dorsolateral view, morphotype with septentrionalis-type distal process terminations, scale bar = 20 µm. 8, plesiotype, AW 1.3 m, Sample 58 (UVic 18-181, slide C, EF: N34/0), right dorsolateral view, morphotype with blunt pseudofurcatus-type distal process terminations and operculum attached, scale bar = 20 µm. 9, specimen originally figured by Drugg (1967, pl. 4, fig. 16) from the Danian of the Moreno Formation, California, as *Cannosphaeropsis filifera* and re-illustrated by Damassa as a paratype (1979, pl. 5, figs. 8, 9); note the apparent pseudofurcatus-type distal process terminations, scale bar = 20 µm (derived from dimensions provided by Drugg (1967, p. 26)). 76

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Plate 5.1. Bright-field photomicrographs and scanning electron micrographs of the calcareous dinoflagellate cyst *Calciadinellum clamosum* subsp. *clamosum* Streng et al., 2004a collected from core sediments recovered from Deep Sea Drilling Project Site 577, Shatsky Rise, northwestern Pacific Ocean. 1–3, specimen without operculum, Sample 3, 112.21 mbsf (UVic 2020-3, slide B, EF G37/4); 1, apical view, archeopyle in focus; 2, mid focus; 3, antapical view. 4–6, specimen with operculum in place, Sample 3, 112.21 mbsf (UVic 2020-3, slide B, EF E29/0); 4, apical view with archeopyle margin in focus; 5, mid focus; 6, antapical view. 7, 8, specimen with operculum in place, Sample 13, 111.61 mbsf (UVic 2020-13, slide A, EF H37/1); 7, lateral view; 8, mid focus. 9, specimen from Sample 2, 112.41 mbsf (UVic 2020-2, stub Se), antapical view. 10, specimen with operculum in place, Sample 2, 112.41 mbsf (UVic 2020-2, stub Se), apicolateral view. 11, specimen without operculum, Sample 2, 112.41 mbsf (UVic 2020-2, stub Se), apicolateral view. 12, specimen without operculum, Sample 15, 111.21 mbsf (UVic 2020-15, stub Sb), apical view. Scale bars = 5 μm 147

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Foreward

Each member of my committee played a unique and crucial role in making my graduate journey possible. In the summer of 2014, Dr. Jim Haggart, who I came to know through the British Columbia Paleontological Alliance, put me in touch with my supervisor, Dr. Vera Pospelova, so that I could begin my M.Sc. studies at the University of Victoria. Vera opened my eyes to the hidden microverse of the fossil record. Dr. Richard Hebda, whom I worked with at the Royal BC Museum, guided me as I bridged the macro- with the microfossil realm during my initial paleontological studies of Hornby Island. Later, as I turned my sights to locating a regional K/Pg boundary, Dr. Jon Husson would provide engaging conversations on stratigraphy that would present me with avenues to establish confidence in my interpretations while challenging me to consider the effects of geophysical and geochemical processes.

An amateur fossil collector who started out with a poli sci degree and wanted to publish a paper on ammonite systematics may have appeared an unorthodox candidate to say the least, but these astounding individuals trusted my ambition and believed in my capacity to carry out the investigations I proposed. To invest in any graduate student is to take on risk and I am ever grateful for their generosity and commitment. Their encouragement, facilitation and nurturing attitude showed me that the thrill of discovery and the prospect of any scientific contribution is in and of itself a fuel to sustain a lifetime in pursuit of greater knowledge. My mom Sheila and my dad Mel fostered my captivation with the natural world from the outset and were behind my aspirations every step of the way. They empowered me with their love, unerring support and connection that I so needed throughout the years.

When my supervisor and now good friend, Dr. Vera Pospelova, relocated to the University of Minnesota in 2019, I would see myself become the last vestige of her laboratory at the School of Earth and Ocean Sciences. In the spring of 2020, the once bustling floors of the Bob Wright Centre would come to carry echoes only in memory and I would find myself wandering those halls of academia like a ghost in transition between worlds; an eerily fitting metaphor realized at times on-site toward the close my doctoral program in the wake of the COVID-19 pandemic. Whatever the future may hold, I believe it must be met with gratitude, humility and the same faith as those who had it in me in their sharing of the tools to chip away at the Great Mystery.

Chapter 1

Introduction

1.1 Paleontological context and previous work

The Cretaceous Period spans 145 to 66 millions years ago (Ma), lasting 79 million years (myr) during which the global environment has varied widely and included oceanic anoxic events and climatic shifts, as evidenced from the fossil and geochemical record (e.g., Mort et al., 2007; Turgeon and Creaser, 2008; Hay and Floegel, 2012). The causal factors underpinning these changes remain the subject of intense research with their relationships to extinctions investigated extensively (e.g., Wan et al., 2003; Föllmi, 2012). Dinoflagellate cysts stand to lay the groundwork toward the resolution of such large-scale paleoenvironmental questions through their use as multi-faceted proxies (e.g., Stover et al., 1996) and usefulness in refining interpretations of marine paleoecosystems and local conditions. However, lack of previous work sees the North Pacific as a major geographical gap in the dataset for the pre-Quaternary palynological record in the Northern Hemisphere, with limited studies of Upper Cretaceous–lower Paleogene marine deposits having been conducted in Japan (e.g., Kurita and Obuse, 1994, 1997) and western North America (e.g., Crickmay and Pocock, 1963; Drugg, 1967; Rouse et al., 1970; Chmura, 1973; Sweet and Mustard, 2003).

The successful application of palynological assemblages for large-scale paleoenvironmental reconstructions requires a basis for accurate regional correlations with other well-studied areas of the world. To date, the biostratigraphic framework for the Cretaceous of the northeastern Pacific region is based largely on range data derived from macrofossil groups such as ammonites (Usher, 1952; Matsumoto, 1960; Jones, 1963; Jeletzky, 1964; Imlay and Jones, 1970; Muller and Jeletzky, 1970; Ward, 1978a, 1978b; Haggart et al., 2005, 2009, 2011; Ward et al., 2012; McLachlan and Haggart, 2018), bivalves (Imlay, 1959, 1961; Jones, 1960; Jeletzky, 1965; Squires and Saul, 2006; Grey et al., 2008; Squires, 2010a) and gastropods (Squires and Saul, 2006; Squires, 2010b), with crinoids only recently used (Haggart and Graham, 2018). Studies of

marine microfossils have also been focused exclusively on foraminiferal (e.g., McGugan, 1964; Sliter, 1973; Dalby et al., 2009) and radiolarian (e.g., Pessagno Jr., 1977; Haggart and Carter, 1993; Carter and Haggart, 2006; Haggart et al., 2009) assemblages in the region. Limited diversity of biological constraints, compounded by faunal endemism and long-ranging taxa in the northeastern Pacific (e.g., Jeletzky, 1965), has proven challenging for relative dating efforts.

1.2 Research objectives and thesis structure

The initial goal of this study is to establish a biostratigraphic framework for the latest Cretaceous–early Paleocene of the North Pacific based on dinoflagellate cysts. From this framework, the objectives are to establish insights into the paleoecology of this phytoplankton group, their temporal and spatial distributions and their associated paleoenvironmental signals in relation to the K/Pg event. The work encompasses four studies placing the region within the global context of the K/Pg boundary interval. Three out of four of the chapters in the body of this thesis were published as independent studies at the time of writing and as such, there is some redundancy in the restatement of materials examined and methods employed. In Chapter 2, the flagship study draws on an analysis of dinoflagellate cysts, acritarchs and pollen and spores extracted from samples throughout three sections of the Oyster Bay Formation in the area of eastern Vancouver Island, British Columbia (BC). This study uses dinoflagellate cyst assemblages to determine the age and extent of the Oyster Bay Formation, a unit which unconformably overlies the strata of the Nanaimo group. Chapter 2 is published in *Cretaceous Research* (McLachlan and Pospelova, 2021). In Chapter 3, the second study address taxonomic revisions within the genus *Cannosphaeropsis* based on material recovered from the Oyster Bay Formation and a literature review of all accepted species therein. Chapter 3 is published in *Review of Palaeobotany and Palynology* (McLachlan et al., 2021). In Chapter 4, the third study focuses on a new species of protoperidinioid dinoflagellate cyst from the Oyster Bay Formation with potential biostratigraphic utility and is published in *Palynology* (McLachlan, 2021). In Chapter 5, the final study examines calcareous dinoflagellate cyst assemblages across the K/Pg boundary from an oceanic setting at DSDP Site 577, Shatsky Rise, in the western North Pacific. Chapter 5 has been submitted to *Marine Micropaleontology*. The thesis concludes with a brief

summary in Chapter 6, reflecting on the findings in each of these studies within a regional and global context.

1.3 Background

Dinoflagellates are single-celled microscopic marine organisms which are a major group of phytoplankton in modern oceans. Dinoflagellates make their first unequivocal appearance in the fossil record during the Triassic Period (e.g., Fensome et al., 1996; Riding et al., 2010) and were largely unaffected on a global scale by the end-Cretaceous extinction event at 66 Ma (e.g., Brinkhuis and Zachariasse, 1988; Fensome et al., 1996; Slimani et al., 2010). Their success in a multitude of environments is reflected in their cysts being highly abundant, widely distributed, and well-preserved in the fossil record (e.g., Sarjeant, 1974; Fensome et al., 1993; Dale, 1996, 2001).

Dinoflagellate cysts are the organic-walled structures produced when the dinoflagellate enters a resting stage following sexual reproduction (e.g., Fensome et al., 1996). In modern taxa, cysts are known to be produced by 13 to 16% of all species (Head, 1996). They are resistant to degradation from chemical and physical processes given their composition, owing to the strength of the carbohydrate-based biomolecule dinosporin (e.g., Fensome et al., 1993; Bogus et al., 2012, 2014). As a consequence of dinoflagellate cyst abundance, assemblage distribution and good preservation, they have been used extensively as indicator fossils for Mesozoic and Cenozoic marine sedimentary rocks for relative dating and stratigraphic correlation, also serving as proxies for reconstructing paleolatitudes and paleoenvironments (e.g., Stover et al., 1996; Bowman et al., 2013; Machalski et al., 2016).

The use of dinoflagellate cysts as paleoenvironmental indicators in ancient marine sediments remains limited to ecogrouping, modern analogues, structural morphology and character expressions, with the integrity of their original biopolymer composition presumed to be unreliable for inferences relating to feeding strategies based on extant forms (e.g., Bogus et al., 2012). Classificatory approaches to fossil dinoflagellate cysts are likely to remain based exclusively on morphological characters that follow descriptive conventions relating to plate arrangement, archaeopyle geometry (the shape of the aperture through which the motile cell

emerged), ornamentation and process types (e.g., Kofoed, 1911; Stover and Evitt, 1978; Wilson and Clowes, 1980; Evitt, 1985). It is these parameters which have formed the foundation of dinoflagellate cyst micropaleontological study since its inception in the mid- to late 19th century (e.g., Ehrenberg, 1837; Mantell, 1854).

1.3.1 Marine palynological approaches through deep time

1.3.1.1 Dinoflagellate cyst paleoproductivity signal

High dinoflagellate cyst concentrations and elevated species richness are considered to be factors indicative of elevated nutrient availability and primary productivity in both modern and ancient marine settings (e.g., Dale, 1996; de Vernal, 2009; Pospelova et al., 2008). Cyst concentrations in modern sediments on the order of tens of thousands per gram are considered typical of high productivity environments (e.g., Pospelova et al., 2010). Limited dinoflagellate cyst concentrations data has been collected from deep time records as most studies consider taxa relative abundances with few exceptions exploring paleoproductivity in pre-Quaternary studies of the Cenozoic (e.g., Sangiorgi et al., 2008; Warny et al., 2003) and Mesozoic (e.g., Dodsworth, 2000; McLachlan et al., 2018). However, absolute abundance analysis is common practice in Quaternary studies (e.g., Marret et al., 2001a, 2001b; Matthiessen et al., 2001) when sedimentation rates can be calculated.

Beyond figures of assemblage diversity and absolute abundance, the ratio between predominantly heterotrophic (peridinioid or protoperidinioid) and autotrophic (gonyaulacoid) dinoflagellate cyst taxa—referred to as the P/G ratio—has been applied by late Mesozoic to Quaternary researchers (e.g., Harland, 1973; Lewis et al., 1990; Guasti et al., 2006; De Schepper et al., 2018) as a paleo-upwelling signal (e.g., Powell et al., 1992; Harland, 1973; Dale and Fjellsa, 1994). The basis of this signal is anchored in the premise that greater heterotroph numbers occur as a result of increased abundances of prey, such as diatoms and other primary producers. Additionally, increases in peridinioid relative or absolute abundance are especially useful when biogeneic silica—a proxy indicative of diatom abundances—is not preserved (e.g., Firth, 1996; Price and Pospelova, 2011). Zonneveld et al. (2007, 2008) emphasized caution in applying a P/G ratio as peridinioid dinoflagellate cyst preservation may be affected by aerobic

degradation. However, most studies in the Pacific region (e.g., Pospelova et al. 2008) have shown that this is not the case in highly productive regions with high sedimentation rates.

1.3.1.2 *Dinoflagellate cyst paleotemperature signal*

The best analogue technique transfer functions and multivariate statistical analyses have enabled past sea-surface temperature reconstructions in Quaternary studies (e.g., Imbrie and Kipp, 1971; Guiot, 1990; de Vernal et al., 1997). With low sampling resolution frequently challenging the accuracy of these techniques in Late Cretaceous–early Paleogene studies, inferences as to lowering sea-surface temperature, for example, have been made based on the spread of typically boreal taxa into more temperate or subtropical regions (e.g., Brinkhuis and Biffi, 1993; Brinkhuis et al., 1998; Vellekoop et al., 2015). The extinction of the peridiniacean *Svalbardella* during the Oligocene (Sluijs et al., 2005) is one such bioevent. The global *Apectodinium* acme is another, illustrating the Paleocene–Eocene Thermal Maximum (e.g., Bujak and Brinkhuis, 1998). These interpretations are based on presumptions of dinoflagellate latitudinal preferences and thus reflect global temperature gradients or ‘climate zones’ (e.g., Mudie and Harland, 1996). These temperature related latitudinal preferences are demonstrated through statistical analyses (e.g., Hill and Gauch, 1980) of modern dinoflagellate cyst assemblages (Marret and Zonneveld, 2003).

1.3.1.3 *Dinoflagellate cyst salinity signal*

Dinoflagellate cyst morphology lending to a sea-surface salinity (SSS) signal has been observed in modern cyst assemblages. Low-salinity conditions are indicated by structural characteristics such as endocyst ambital geometry (internal body profile) (e.g., Wall et al., 1973, 1977; Wall and Dale, 1974) and reduced process length (e.g., de Vernal et al., 1989; Lewis et al., 1999; Head, 2007). However, many unknown variables are at play in early Cenozoic assemblages and make it difficult to reconstruct ancient SSS. Such interpretations become even more uncertain when consideration is given to studies involving the culture of extant species. Unknown factors have been considered likely to influence dinoflagellate cyst morphology because forms vary under stable laboratory conditions (e.g., Kokinos and Anderson, 1995; Lewis et al., 1999) and depend on provenance (Jansson et al., 2014). Potentially the most reliable

dinoflagellate cyst SSS proxy—at least throughout much of the Paleogene—is the abundance of the *Homotryblum* complex if only by virtue of its morphological affinity with the extant genus *Polysphaeridium*, known for its association with low-salinity environments (e.g., Brinkhuis, 1994; Sluijs et al., 2005).

Dinoflagellate cyst paleoenvironmental studies benefit from the established basis of extant morphometric groups confirmed to be indicative of specific SSS conditions (e.g., Popescu et al., 2009), such as members of several genera including *Serilodinium*, *Spiniferites* and *Thalassiphora*, which develop a cruciform (ambital) profile with low salinity (e.g., Rochon et al., 2002; Popescu et al., 2009; Ferguson et al., 2018). With respect to process development as a metric of SSS, process length in the species *Lingulodinium machaerophorum* is most frequently employed with long spines indicative of reduced salinity and shortened, bulbous projections as a reflection of higher salinity conditions (e.g., Mudie et al., 2001; Mertens et al., 2009a; Ferguson et al., 2018). This relationship between process development and SSS is understood to represent a response to water density variance with an increase in dinoflagellate cyst surface area inferred to be an adaptation to maintain suspension in the water column.

1.3.1.4 Dinoflagellate cyst shore proximity and eustacy signals

Inferences of shore proximity and glacio-eustatic fluctuation are made possible through obtaining a marine to terrestrial palynomorph ratio (e.g., McCarthy and Mudie, 1998; McCarthy et al., 2003; Crouch et al., 2010), as well as a ratio of dinoflagellate cyst taxa with known neritic compared to pelagic habitat preferences (e.g., Peeters et al., 1996; Warny and Wrenn, 2002; Eldrett and Harding, 2009; Zonneveld et al., 2013). The latter approach was formulated based on the habitat differential between gonyaulacoid genera—namely, the oceanic prevalence of *Impagidinium* and *Nematosphaeropsis* in contrast to the neritic predisposition of *Spiniferites* in modern marine assemblages as first observed by Wall et al. (1977). These taxa are also present throughout the Late Cretaceous–Paleogene fossil record and therefore provide a potential gauge for the neriticity of depositional settings (e.g., Brinkhuis, 1994; Sluijs et al., 2008a). Where these taxa are geographically absent or underrepresented, morphologically analogous forms belonging to similarly long-ranging groups or complexes—such as members of the genera *Areoligera* and

Glaphyrocysta—have been widely utilized in Late Cretaceous and early Paleogene studies (e.g., Downie et al., 1971; Powell et al., 1996; Soliman, 2012).

Similar to the generalist approach toward character utility in dinoflagellate cyst morphostratigraphy (Monteil, 1990, 2005), the determination of paleoshore proximity often employs the concept of ‘ecotypes’ or ‘ecogroups’ (e.g., Sluijs and Brinkhuis, 2009; Iakovleva, 2015; Shcherbinina et al., 2016). This approach avoids the potential pitfalls of species-level taxonomic ambiguity. The predominant nearshore occurrence of many chorate forms such as the areoligeracean *Cyclonephelium* as well as the cribroperidinioids *Exochosphaeridium* and *Operculodinium* has been demonstrated (e.g., Powell et al., 1996; Harris and Tocher, 2003; Peyrot et al., 2012) and used to further refine the understanding of preferential positioning along a shelf transect (e.g., Brinkhuis, 1994; Pross and Brinkhuis, 2005; Sluijs et al., 2005). The establishment of proximal–distal trends also helps detect sea level change, with inferences based primarily on the ratio of oceanic to neritic dinoflagellate cyst groups (e.g., Brinkhuis and Zachariasse, 1988; Firth, 1993; Eldrett and Harding, 2009).

1.4 Regional setting and geology

1.4.1 Cretaceous and lower Paleogene stratigraphy of British Columbia

Extensive exposures of Cretaceous rocks are present within the Insular Belt of the Canadian Cordillera, scattered along coastal BC (e.g., Monger et al., 1994; Enkin et al., 2003). A nearly complete Cretaceous succession can be considered through aggregation of three key rock packages present on Haida Gwaii, Vancouver Island and Grassy Island, off the northwest coast of Vancouver Island. Lower Cretaceous strata are represented in the Queen Charlotte and Kyuquot groups exposed on Haida Gwaii as well as the One Tree and Longarm formations of the Kyuquot Group on Grassy Island (Jeletzky, 1965; Muller et al., 1981; Haggart, 1991, 1993; Grey et al., 2007, 2008). Upper Cretaceous strata are represented within the Queen Charlotte Group (Haggart et al., 2009) of Haida Gwaii and the Nanaimo Group Vancouver Island and the Gulf Islands (e.g., Mustard, 1994; Katnick and Mustard, 2003; Haggart et al., 2005; Bain and Hubbard, 2016). Relative dating of these rock packages has to date been based principally on molluscs (e.g., Jeletzky, 1950, 1965, 1970; Usher, 1952; Muller and Jeletzky, 1970; Haggart et

al., 2005, 2011, McLachlan and Haggart, 2018; Ward, 1978a, 1978b; Ward et al., 2012), crinoids (Haggart and Graham, 2018), foraminifera (McGugan, 1962, 1964, 1979, 1982; Sliter, 1973; Dalby et al., 2009; Patterson et al., 2010), radiolarians (Haggart and Carter, 1993; Carter and Haggart, 2006) and dinoflagellate cysts (McLachlan et al., 2018), magnetostratigraphy (Raub et al., 1998; Enkin et al., 2001; Ward et al., 2012) and geochemical (Zakharov et al., 2013; Jenkins et al., 2017) age controls.

Unrelated to the Pacific coast successions, major Lower Cretaceous marine rock packages are present in the northeastern BC interior, represented in the Bullhead, Fort St. John and Minnes groups. The Jurassic–Cretaceous boundary lies in the beds transitional from the Fernie Formation to the Minnes Group which ranges into the Valanginian (Stott, 1998). Succeeding these strata are rocks of the Barremian–Aptian Bullhead Group and the lower Albian–Cenomanian Fort St. John Group (e.g., Stott, 1968, 1982). An incomplete Upper Cretaceous marine succession is represented by the Smoky Group in northeastern BC, which encompasses the middle Cenomanian Dunvegan Formation (e.g., Bhattacharya, 1994), the Cenomanian–middle Turonian Kaskapau Formation (e.g., Kilby and Wrightson, 1987), the Turonian–Coniacian Cardium Formation (e.g., Hart and Plint, 2003) and the Santonian–lower Campanian Puskwaskau Formation (e.g., Fanti and Catuneanu, 2009). Non-marine deposits of the upper Campanian–lower Maastrichtian Wapiti Formation are also present in easternmost BC extending into west-central Alberta (e.g., Fanti and Catuneanu, 2009). Several formations in the Peace region have gained recognition for their wealth of dinosaur fossils and trackways (e.g., Rylaarsdam et al., 2006; Fanti et al., 2013; McCrea et al., 2015).

To the west of the ancestral Rocky Mountains, a nearly complete composite Lower Cretaceous package is also represented in the southwestern BC interior by the Jackass Mountain, Taylor Creek and Relay Mountain groups (e.g., Maclaurin et al., 2011). Other Lower Cretaceous successions also occur in southern BC, such as the potentially lowermost Cretaceous non-marine Mist Mountain Formation of the Kootenay Group (e.g., Gibson, 1985) and the non-marine Albian Pasayten Group (e.g., Coates, 1974). The Bowser Basin in northern BC contains the Barremian–Albian McEvoy Formation as well as Bowser Lake Group units of the mid-Albian–Cenomanian Devils Claw Formation and the possibly Albian–Campanian Tango Creek Formation (e.g., Cookenboo and Bustin, 1988).

Exposures of early Paleogene strata are sparse in the northeast Pacific and no conformable K/Pg boundary section has been formally documented in the region (e.g., Hopkins, 1966; Rouse et al., 1970, 1975). Packages of late Paleocene–middle Eocene rocks are represented by the Huntingdon Formation within the Lower Mainland of BC and the Chuckanut Formation of northwestern Washington State (e.g., Johnson, 1984; Mustoe and Gannaway, 1997; Mustoe et al., 2007) which unconformably overlie Upper Cretaceous Nanaimo Group strata scattered across eastern Vancouver Island (examined herein) and the Gulf Islands (Mustard and Rouse, 1994). Occurrences of outlying sandstones of reported late Paleocene age have been described on Lasqueti Island (Mustard and Rouse, 1991), Tumbo Island and the Sucia Island chain (Mustard and Rouse, 1992). Other successions of Paleocene–Eocene age in the BC interior are found in the Brothers Peak Formation, Sustut Group (e.g., Cookenboo and Bustin, 1988), as well as the early to middle Eocene lake sediments of the Allenby Formation, Princeton Group (e.g., Dillhoff et al., 2013), the middle Eocene Kishenehn Formation in southern BC (e.g., Pierce and Constenius, 2014) and early Eocene McAbee beds of the Tranquille Formation, Kamloops Group which have yielded extensive paleobotanical and paleoentomological assemblages (e.g., Gushulak et al., 2016).

1.4.2 Study area

Two locations have been selected within the North Pacific region for investigation: the Oyster Bay Formation of eastern Vancouver Island, BC, Canada, in the northeastern Pacific and DSDP Site 577 on Shatsky Rise in the northwestern Pacific. The former, characterized by exposures of mudstone to conglomerate beds, is the primary focus of this thesis. It consists of a sedimentary rock unit which unconformably overlies the Upper Cretaceous Nanaimo Group and is known only from limited exposures south of Campbell River (see Fig. 2.1). The lithology ranges from mudstone to sandstone with rare conglomerate beds. Paleobotanical research (e.g., Mindell et al., 2014; Buczkowski et al., 2016; Mindell pers. comm., 2018) has placed the Appian Way beds of the formation in the Eocene whereas analysis of terrestrial palynomorphs (Sweet, 1997, 2005), molluscan faunas and detrital zircon U-Pb radiometric dating (e.g., Haggart et al., 2018, in prep; Haggart pers. comm., 2018) have suggested a Paleocene age. Based on the dinoflagellate cyst work herein, the formation is now understood to represent among the oldest post-Cretaceous

strata in the region. Resolution of the age of the Appian Way beds in relation to those of the nearby Lynnwood locality and Oyster River provide confirmation of the localized extent of the post-Cretaceous package in relation to the underlying Nanaimo Group succession. The latter site in this investigation consists of a hydraulic piston core recovered from DSDP Site 577 obtained at Shatsky Rise in the northwest Pacific (Fig. 5.1). This core has yielded a continuous, undisturbed sequence of nannofossil ooze (> 90% CaCO₃) across the K/Pg boundary (e.g., Wright et al., 1985; Zachos et al., 1989).

1.5 Materials and methods

1.5.1 Sampling and preparation

Samples from the Oyster Bay Formation were collected over multiple field expeditions during the summer months of 2018 and 2019, spanning the entirety of the exposed sections along the Oyster Bay coastline and the Oyster River. With the exception of a few float matrices, in-situ subsurface samples were extracted from outcrops via hand tools or a portable drill to avoid modern palynological contaminants. Samples were obtained at 1–4 m intervals throughout most of the formation. Samples from across the K/Pg boundary interval from the DSDP Site 577 core from Shatsky Rise, were obtained from the Gulf Coast Repository, Texas A&M University, College Station, Texas.

Sample preparation for organic-walled dinoflagellate cysts follows a process wherein <3 cm³ of matrix are thoroughly washed, placed in 50 ml test tubes, and treated using a palynological procedure involving acid treatment to dissolve the mineral matrix (e.g., Pospelova et al., 2005, 2010; Mertens et al., 2009b). The dry weight of the samples is recorded and samples are then treated repeatedly with 10 ml of 10% room-temperature hydrochloric acid (HCl) to dissolve the carbonates. One *Lycopodium clavatum* tablet is added to each sample to allow for estimates of palynomorph concentrations (e.g., Benninghoff, 1962; Stockmarr, 1971; Mertens et al., 2009b, 2012c). Following HCl, the samples are sieved through a 15 µm nylon screen prior to being treated with 48% room-temperature hydrofluoric acid (HF). Afterward, each sample undergoes one HCl treatment and two rinses of reverse osmosis water to remove HF residue before final sieving through 120 µm and 15 µm mesh to remove sediment particles and recover

palynomorphs. Samples receive up to one minute of ultrasonic agitation (Mertens et al., 2012c) and are then centrifuged at 3600 rpm. Residue is subsequently mounted in glycerin jelly on microscope slides for bright-field microscopy or on aluminum stubs for scanning electron microscopy (SEM).

1.5.2 Dinoflagellate cyst identification and abundance analysis

Dinoflagellate cysts were identified to the species level wherever possible with taxonomy and nomenclature following that of Fensome et al. (2019). The conventional Kofoed Tabulation System (Kofoed, 1907a, 1907b, 1909, 1911) was employed in plate identification and naming. Relative abundance estimates for both marine and terrestrial palynological constituents were calculated as percentages of the total counted dinoflagellate cysts and grains of pollen and spores. For high-diversity assemblages, a minimum of 400 cysts were counted over a maximum of four slides where possible, a number targeted in several previous K/Pg interval studies (Slimani et al., 2010, 2016) and well above the minimum deemed necessary for statistical purposes (Harker et al., 1990). Palynomorphs were identified and counted if more than half of a specimen was intact (operculum notwithstanding in dinoflagellate cysts), including bisaccate pollen central bodies plus one bladder, and trilete spores of at least two-thirds. Following the acid treatment procedure for organic-walled dinoflagellate cyst recovery, foraminiferal organic linings, acritarchs and all outlying palynomorphs were also counted to provide comprehensive assemblage surveys. Terminology relating to classes of relative abundance follow the parameters of Pospelova et al. (2004): present (>0–1%); rare (>1–5%); common (>5–30%); abundant (>30–50%); dominant (>50%). Estimates of absolute dinoflagellate cyst and pollen and spore abundances were calculated using the formula of Benninghoff (1962): $C = \frac{d_c \times L_t \times t}{L_c \times w}$ where C is the concentration of dinoflagellate cyst or pollen and spores (per g⁻¹ of sediment), d_c is the number of counted dinoflagellate cysts, L_t is the number of *Lycopodium* spores per tablet, t is the number of tablets added to the sample, L_c is the number of counted *Lycopodium* spores and w is the weight of dried sediment (g) (see: Mertens et al., 2012c).

1.5.3 Data presentation and statistical analysis

Photographs were taken at 600x or 1000x magnification using a Nikon Eclipse 80i light microscope with a Nikon DS-5M-L1 digital camera system. Bright-field photomicrographs of specimens were arranged into plates using Macromedia Fireworks 8 software (Adobe Systems Inc., San Jose, CA, USA). For clarity of presentation, extraneous particulate debris was electronically removed from the image (Riding and Head, 2018). Using a Nikon Intensilight C-HGFI precentered fiber illuminator, epifluorescence analysis was conducted on selected dinoflagellate cysts to establish primary production capability (e.g., Wood, 1955; Lessard and Swift, 1986; Pospelova and Head, 2002). Scanning electron microscopy analysis and focused ion beam ablation took place through the Advanced Microscopy Facility (University of Victoria, Victoria, Canada) using a Hitachi S-4800 SEM and Hitachi FB2100 focused ion beam. Adobe Illustrator CS2 software was used to produce myriad illustrative figures and schematic diagrams based on the measured sections in each study area, with their lithology and sample positioning plotted to provide a visual framework against which assemblage and geochemical trends were plotted. Paleoecological inferences were made through use of several software programs to assist in the computation and presentation of statistical data. Tilia 2.6.1 software (Grimm, 1991–2019) was used for generating bar charts and CONISS cluster analysis diagrams which were then adjusted for optimal presentation in Adobe Illustrator CS2. In addition to species richness, the diversity of the dinoflagellate cyst assemblages was calculated using both Shannon-Wiener and Gini-Simpson indexes (e.g., Gini, 1912; Simpson, 1949; Shannon and Weaver, 1949; Jost, 2006).

1.6 Research significance

Extensive research has been conducted to elucidate paleoecological responsiveness and paleoenvironmental conditions before and following the global K/Pg extinction event (e.g., Alegret et al., 2012; Vajda and Bercovici, 2014; Witts et al., 2016). Conformable K/Pg boundary successions are known around the world (Claeys et al., 2002; Kiessling and Claeys, 2002) with the Global Stratotype Section and Point for the boundary having been placed in El Kef, Tunisia (Molina et al., 2006). Dinoflagellate cysts, along with other biological and geochemical proxies, have been examined extensively at the Tunisian type section (Brinkhuis and Zachariasse, 1988;

Brinkhuis et al., 1998; M’Hamdi et al., 2015; Vellekoop et al., 2015) and at numerous other locations in the Northern Hemisphere (e.g., Europe: Slimani et al., 2011; Smit and Brinkhuis, 1996; Machalski et al., 2016; Africa: Slimani and Toufiq, 2013; Guédé et al., 2014; Slimani et al., 2016; Asia: Erkmén and Sadek, 1981; Beiranvand et al., 2014; Açikalin et al., 2015) and Southern Hemisphere (e.g., Askin, 1988; Willumsen, 2011; Vellekoop et al., 2017). In North America, marine palynological studies across K/Pg boundary intervals have been restricted to the Western Interior (McIntyre, 1999; Prauss, 2009; Oboh-ikuenobe et al., 2012) and US eastern seaboard (e.g., Moshkovitz and Habib, 1993; Habib and Saeedi, 2007; Vellekoop et al., 2016).

No marine palynological work has been done across a K/Pg boundary in the North Pacific realm, although nannofossil and foraminiferal studies have been conducted using cores with continuous K/Pg sections obtained from the central North Pacific (Schulte et al., 2010), encompassing those from Deep Sea Drilling Project (DSDP) and Ocean Drilling Program sites 465, 576, 577, 886, 1209–1212 (e.g., Kyte et al., 1995; Premoli Silva et al., 2005) and piston core LL44-GPC3 (Doh et al., 1988). A continuous, biostratigraphically complete K/Pg boundary succession at a terrestrial site in the North Pacific realm is known only from Japan and is based on planktic foraminifera and terrestrial sporomorphs (Saito et al., 1986; Mita and Shimoyama, 1999). Elsewhere in the region, K/Pg intervals have been reported from the Russian Far East (Koryak Upland: Golovneva, 1994; Sakhalin Island: e.g., Zakharov et al., 1996; Shigeta and Maeda, 2005) and northern Alaska (e.g., Waller and Marincovich Jr., 1992; Marincovich Jr., 1993), although these sites have yet to be resolved by well-constrained biostratigraphic controls.

In western North America outside of BC, strata of latest Cretaceous age have been identified in the lower Maastrichtian Matanuska and Kaguyak formations in southern Alaska, based on molluscan fossils (Jones, 1963). Most of the rocks near the K/Pg boundary, however, are present in California where the interval is demarcated by the approximately conformable boundary between the Marca Shale and Dos Palos Shale members of the Moreno Formation within the Great Valley sequence (e.g., Schwartz et al., 2003). Elsewhere in California, strata of Danian age (Franciscan Complex: Damassa, 1979b; Martinez Formation: e.g., Saul and Squires, 1997; San Fransiquito Formation, other unnamed units: e.g., Squires and Saul, 1993; Squires, 1997) unconformably overlie lower Maastrichtian deposits in the Chatsworth, Panoche and Point Loma formations (e.g., Squires and Saul, 2001). In Baja California, the Danian Sepultura Formation

(Téllez Duarte and López Martínez, 2002) is seen to unconformably overlie the upper Maastrichtian Rosario Formation (Li et al., 2018).

From a marine palynological standpoint, key biostratigraphic markers for the K/Pg boundary interval are the upper range limits of the cosmopolitan dinoflagellate cyst index taxa *Palynodinium grallator* and *Dinogymnium* spp., demarcating the upper Maastrichtian (e.g., Hansen, 1977; FitzPatrick et al., 2017; Țabăra et al., 2017), succeeded by the basal Danian indicators *Dania californica* and *Senoniasphaera inornata* (e.g., Miller et al., 2010; Guédé et al., 2014; Slimani et al., 2016). In the early stages of my investigation, samples from the stratigraphically highest beds of the Nanaimo Group represented by the sandstones of the upper Maastrichtian Gabriola Formation were collected from the syncline axis on Gabriola Island and found to be barren of dinoflagellate cysts. However, the presence of K/Pg index taxa within the Oyster Bay Formation of eastern Vancouver Island were confirmed following my pilot analysis of the sedimentary rocks exposed at the coastal outcrop herein described as the Lynnwood section. Based on the resolution of the sampling conducted during my preliminary investigation, it can be stated with confidence that a stratigraphically expanded K/Pg boundary interval can be constrained to within several metres at the Lynnwood locality.

The acquisition of continuous phytoplankton data across the K/Pg interval in the North Pacific is a valuable addition to the global dataset given the paleobiogeographic challenges posed by macrofossil endemism (e.g., Matsumoto, 1960; Jeletzky, 1965; Frederiksen, 1987; Jagt-Yazykova, 2012; Jonsson and Hebda, 2015), which have obstructed efforts toward regional correlation resulting in the need for taxonomic clarification. Analysis of the organic-walled and calcareous dinoflagellate cysts within the following studies also has the potential for paleoenvironmental reconstructions of depositional settings and recognition of trends in primary productivity, as revealed through assemblage compositions, specimen concentrations and determined through relative and absolute abundance estimates. Such analyses enable a robust, biostratigraphic control for the uppermost Cretaceous–lower Paleocene strata of the North Pacific independent from other relative dating methods through the establishment of index taxon ranges. Additionally, some dinoflagellate cyst groups are yet to have the extent of their utility fully realized in broader practice as morphological variations are being reinterpreted through the lens of ecophenotypy, following earlier investigations (e.g., Evitt, 1985; McLachlan et al., 2019); conceptualization which stands to refine high resolution paleoenvironmental interpretations.

Chapter 2

Dinoflagellate cyst-based paleoenvironmental reconstructions and phytoplankton paleoecology across the Cretaceous–Paleogene (K/Pg) boundary interval, Vancouver Island, British Columbia, Canada¹

2.1 Contributions of authors

All of the content presented herein—from conceptualization to the figures, data, analyses, results, discussions and conclusions—was produced by the lead author. In addition to providing assistance with the methodology, review of the manuscript and funding, Dr. Vera Pospelova assumed an advisory role from which the study benefited greatly given her influence on the data presentation and discussions relating to the ecology of extant species.

2.2 Abstract

A conformable K/Pg boundary succession is reported for the first time in North America west of the Rocky Mountains and in the north-eastern Pacific based on biostratigraphic controls,

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occurring within the upper Maastrichtian–lower Selandian marine sedimentary rocks of the Oyster Bay Formation, Vancouver Island, British Columbia. Approximate placement of the boundary is made possible by a suite of temporally constrained palynological K/Pg interval indicator taxa. The low-diversity, homogenous coastal dinoflagellate cyst assemblages of the *Cordosphaeridium*, *Glaphyrocysta*, *Hystrichosphaeridium* and *Spiniferites*-dominated uppermost Maastrichtian of the Lynnwood section transition to that of a more intermixed estuarine setting dominated by *Areoligera*, *Exochosphaeridium* and *Gingiodinium* along with peaks of low-salinity tolerant *Senegalinium* into the Danian–Selandian strata of the Appian Way and Oyster River sections. A marine assemblage turnover in the middle Oyster Bay Formation under conditions of elevated primary productivity and community heterogeneity owing to nutrient-rich waters is observed. Evidence for this interpretation is reinforced by the presence of overall higher cyst concentrations, peridinioid abundance and greater species diversity in association with botanical and shallow marine invertebrate fossil assemblages. The palynological data record probable eustatic regressive and transgressive sequences which illustrate a history of fluctuation between a predominantly coastal and largely estuarine paleoenvironment punctuated by the end-Cretaceous event. The presence of heavily negative $\delta^{13}\text{C}_{\text{org}}$ values, in addition to facies changes throughout the succession, support a neritic profile for the Oyster Bay Formation. The palynological assemblages reflect localized paleoenvironmental conditions and climatic changes across the K/Pg boundary consistent with observations from numerous localities across both hemispheres.

2.3 Introduction

A great deal of research has been conducted to elucidate paleoecological responses and paleoenvironmental conditions in the wake of the global K/Pg extinction event (e.g., Alegret et al., 2012; Vajda and Bercovici, 2014; Witts et al., 2016). The K/Pg extinction is now interpreted to have resulted from the combination of protracted volcanic eruptions of the Deccan Traps in India (e.g., Keller et al., 2009; Archibald et al., 2010; Sprain et al., 2019) and an extraterrestrial bolide impact (e.g., Alvarez et al., 1980; Hildebrand et al., 1991; Schulte et al., 2010). This cataclysmic ‘one-two punch’ paleoenvironmental event saw the dinoflagellates emerge largely unscathed, likely due to the ecological resilience, abundance and cosmopolitan distribution

among many forms of these unicellular phytoplankton (e.g., Brinkhuis and Zachariasse, 1988; Fensome et al., 1996; Stover et al., 1996; Vellekoop et al., 2015). As a result of these factors, organic-walled dinoflagellate cysts have tremendous utility for relative dating and paleoenvironmental reconstruction in Mesozoic and Cenozoic studies, with much recent application surrounding the K/Pg boundary (e.g., Machalski et al., 2016; Țabără et al., 2017; Vellekoop et al., 2017; Soliman and Slimani, 2019).

Over 350 stratigraphically complete K/Pg boundary sites have been identified worldwide (Claeys et al., 2002) with approximately one-third having documented ejecta debris or evidence of an associated iridium anomaly (e.g., Kiessling and Claeys, 2002; Goderis et al., 2013). In the North Pacific realm, terrestrial exposures of marine K/Pg boundary successions have been identified only in Far East Asia (e.g., Saito et al., 1986; Mita and Shimoyama, 1999; Shigeta and Maeda, 2005). Rock packages of similar age are limited in the north-eastern Pacific occurring at a few locations along western North America, ranging from the North Slope of Alaska (e.g., Frederiksen, 1991; Waller and Marincovich Jr., 1992) to California (e.g., Squires and Saul, 2001; Schwartz et al., 2003) and Mexico (e.g., Helenes and Téllez-Duarte, 2002; Pan Li et al., 2018), but lack either geological conformity or refined biostratigraphic controls. This vast expanse of the Northern Hemisphere has experienced a dearth of marine palynological studies in approach to this interval, which have been limited to California (Drugg, 1967; Damassa, 1979) and Japan (Kurita and Obuse, 1997; Kurita, 2004). Therefore, the acquisition of such data in proximity to the K/Pg boundary is a valuable addition to the global dataset given the paleobiogeographic challenges posed by faunal endemism (e.g., Matsumoto, 1960; Jeletzky, 1965; Jagt-Yazykova, 2012) and floral endemism (Frederiksen, 1987; Jonsson and Hebda, 2015) that have hampered efforts toward regional correlation in Cretaceous research.

Beds of presumed early Paleogene age known from isolated outcrops along eastern Vancouver Island have yielded a highly rich macrofossil assemblage consisting of flora which has been extensively examined (Ludvigsen and Beard, 1994, 1998; Smith et al., 2004; Hernandez-Castillo et al., 2005; Trivett et al., 2006; Mindell et al., 2006a, b, 2007a, b, 2009, 2014; Elliott et al., 2006; Rankin et al., 2008; Steenbock et al., 2011; Atkinson et al., 2015; Buczkowski et al., 2016; Mustoe and Beard, 2021), along with diverse faunal collections of decapod (Ludvigsen and Beard 1994, 1998; Schweitzer et al., 2003, 2009; Nyborg et al., 2015, 2019) and molluscan (Haggart et al., in prep.) material. Previous palynological reports have

provided only a cursory overview of terrestrial assemblages from limited samples (Sweet, 1997, 2005). Despite the wealth of knowledge that has been gleaned from this namely paleobotanical Lagerstätte, no adequate micropaleontological techniques have been applied to the marine planktonic fossil record preserved within this unit. Using dinoflagellate cysts and limited geochemical analyses, this study aims to establish resolution of the age, depositional setting, phytoplankton paleoecology and paleoenvironmental conditions under which these Vancouver Island deposits were laid down.

2.4 Geological setting

Exposures of uppermost Cretaceous–lower Paleogene strata are sparse in the north-eastern Pacific and no conformable K/Pg boundary section has been documented in the region (e.g., Rouse et al., 1970, 1975). Packages of lower Paleocene–middle Eocene rocks within lower mainland British Columbia (BC) and north-western Washington State, represented by the Huntingdon and Chuckanut formations respectively (e.g., Johnson, 1984; Mustoe and Gannaway, 1997; Mustoe et al., 2007; Miller et al., 2009; Mathewes et al., 2020), unconformably overlie those of the Upper Cretaceous Nanaimo Group scattered across eastern Vancouver Island and the Gulf Islands (Mustard and Rouse, 1994). Beds correlative with the Chuckanut Formation are present on Tumbo Island (Muller and Carson, 1969), with continuity across the Sucia Island chain (Mustard and Rouse, 1992, 1994; England et al., 1997). Elsewhere in the Strait of Georgia, occurrences of outlying sandstones of possible Paleocene age have been described on Lasqueti Island (Stewart and Page, 1974; Mustard and Rouse, 1991), as well as on the adjacent Marine and Sangster islands (Muller and Carson, 1969). Paleobotanical studies of the Oyster Bay strata found the flora of the colloquially ascribed Appian Way locality to be broadly correlative with that of Eocene sites from other regions (e.g., Mindell et al., 2007a, 2009, 2014), while preliminary investigations provided dating estimates ranging from late Paleocene based on terrestrial palynomorphs (Sweet 1997, 2005) to middle Eocene based on molluscs, decapods and shark teeth (e.g., Haggart et al., 1997; Cockburn and Haggart, 2007); an age range approximation maintained by Haggart et al. (in prep.).

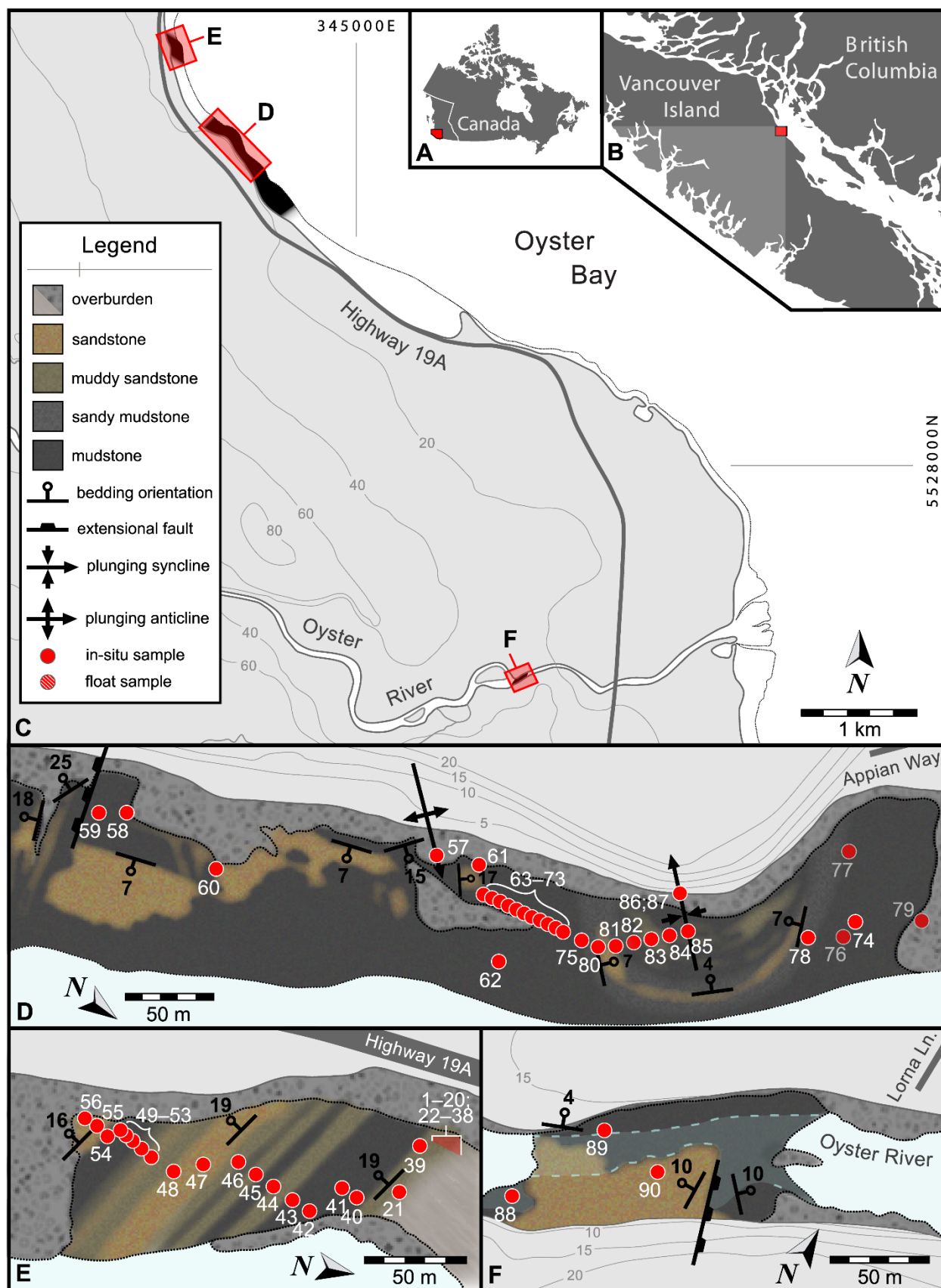
Assignment of the Oyster Bay area strata to a formation of the namesake was first informally proposed by England (1990), with presumed equivalence to the Upper Cretaceous beds of Shelter Point previously described to the north (Richards, 1975; Ward, 1978). This approach was largely sustained (Ludvigsen and Beard, 1998; England and Bustin, 1998), although Cathyl-Bickford and Hoffmann (1998) assigned much of the coastal section to the Denman and Lambert formations within the nomenclature of the dual basin model for the Nanaimo Group strata (England and Bustin, 1998), presumably due to the presence of expansive fine-grained beds. Current practice favours acceptance of the singular Nanaimo Basin model (e.g., Mustard, 1994; Katnick and Mustard, 2003; Bain and Hubbard, 2016). However, the move toward formal establishment of the Oyster Bay Formation, which later came to be used to distinguish the beds of the Appian Way locality (Mindell et al., 2006a, b, 2009; Rankin et al., 2008; Steenbock et al., 2011; Atkinson et al., 2015; Mustoe and Beard, 2021) has transpired only recently (Haggart et al., in prep.). As a whole, the package is now understood to comprise a ~93.5 m-thick marine succession with a lateral extent over at least 6.5 km as delineated from three exposures (Fig. 2.1C).

2.4.1 Lynnwood section

The 48.2 m-thick Lynnwood section represents the lower portion of the Oyster Bay Formation, which is comprised of conglomeratic sandstone to mudstone interbeds. The unit is exposed over 200 m along the eastern shore of Vancouver Island at Oyster Bay, south of Campbell River, situated opposite Lynnwood Road (Fig. 2.1E). At its top, the Lynnwood section bears a lithological similarity to the base of the Appian Way section due to the presence of a distinctive cobble-bearing conglomeratic sandstone. A similar conglomeratic sandstone bed is exposed on the downthrown side of the fault 240 m to the south-east of the Appian Way anticline axis. However, folding and factors of lateral displacement preclude direct lithological correlation between the top 5 m of the Lynnwood section and the bottom 5 m of the Appian Way section.

2.4.2 Appian Way section

Exposures of the Appian Way locality consist of a ~43 m-thick section of mudstone to



← **Figure 2.1.** **A**, Location of Vancouver Island, British Columbia, Canada. **B**, Location of study area, east coast Vancouver Island. **C**, Oyster Bay Formation localities; red boxes denote extent of studied coastal (**D**, **E**) and Oyster River (**F**) exposures. **D**, structural geology, lithology and sample locations at the Appian Way coastal outcrop. **E**, structural geology, lithology and sample locations at the Lynnwood coastal outcrop. **F**, structural geology, lithology and sample locations along the Oyster River (shoulders at lowest seasonal discharge indicated by dashed blue lines).

sandstone interbeds extending conformably for 1.2 km along the coast, situated approximately 700 m to the south-east of the Lynnwood outcrop (Fig. 2.1D) . The outcrop is predominantly located within the intertidal zone underlying a 12.5 m-high cliff forming the topographic high of the syncline axis. Due to limited accessibility, only the basal 2.5 m of the embankment above the high tide mark was included in the studied section with samples having been extracted from the muddy sandstone which underlies the massive sandstone cliff face. South of the Appian Way roadway and north of Sailor Road exists the greatest visible horizontal extent of the upper section of the Oyster Bay Formation.

2.4.3 Oyster River section

Lastly, an isolated exposure of the Oyster Bay Formation is present at the terminus of the Lorna Lane roadway ~2 km upstream from the mouth of the Oyster River (Fig. 2.1F). The Oyster River section is quite limited, being 2.3 m-thick and restricted to narrow outcrops along the north and south shoulders of the river over a 200 m distance amounting to <3000 m² in surface area at lowest river discharge. General correlation between the Oyster River exposure and the Appian Way section is possible based on petrography and macrofossils (Haggart et al., in prep.), as well as the microfossil assemblages examined herein. However, precise stratal positioning of the Oyster River beds is still problematic due to regional folding and faulting, although the aforementioned biostratigraphic evidence provides strong indication that they unconformably overlie those of the coast.

2.5 Materials and methods

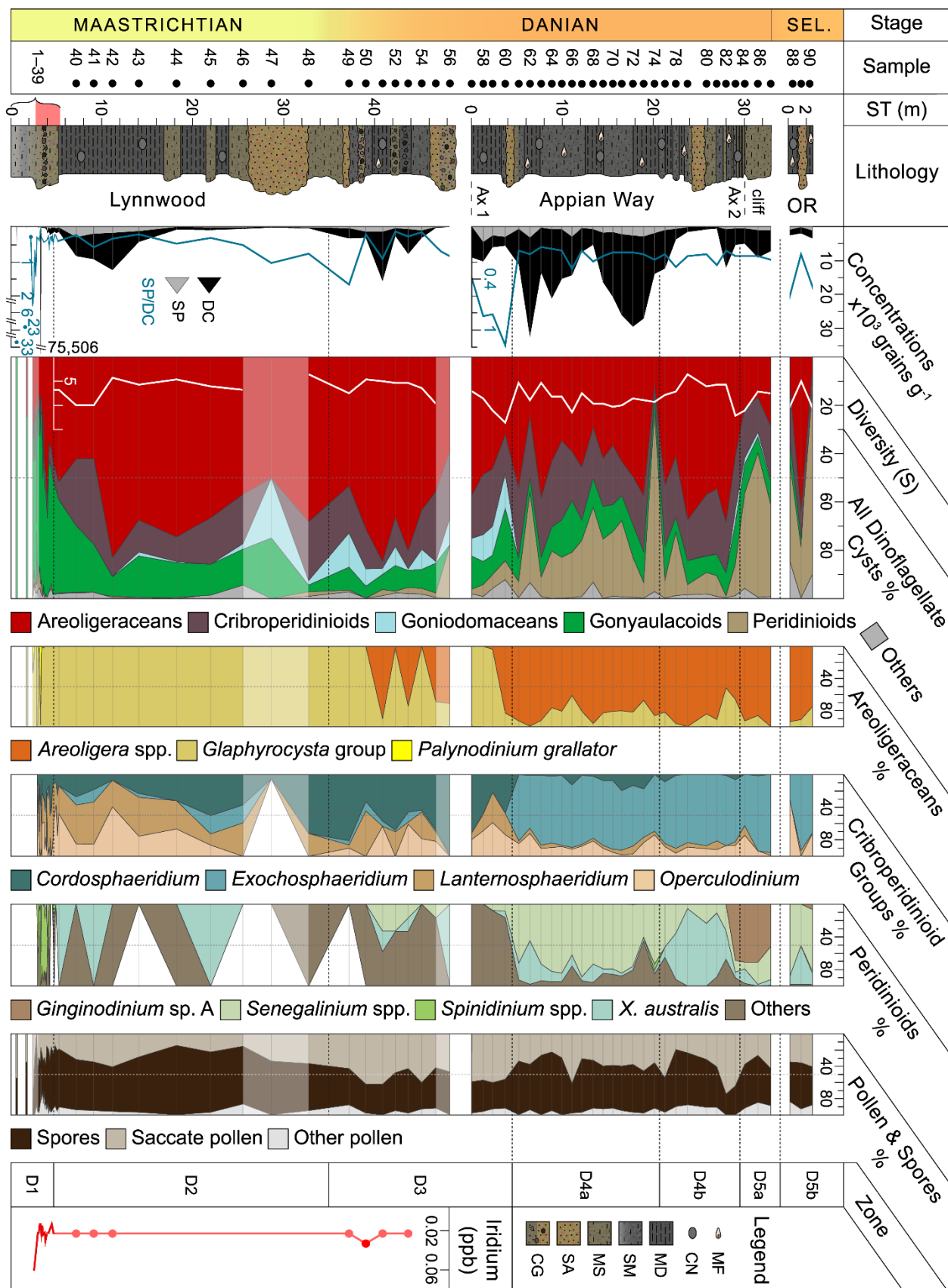
2.5.1 Palynology

2.5.1.1 Collection

A total of 90 sedimentary rock samples were collected from exposures of the Oyster Bay Formation and processed for palynological analysis; 56 from the Lynnwood section, 31 from the Appian Way section and three from the Oyster River section. Three of the Appian Way samples were collected from float concretionary mudstone matrices during the pilot phase of this study. Thirty-nine samples were extracted over 5.3 m above the base of the Lynnwood section using a 1-3/4" diameter core drill and hand tools with an accuracy of ± 2.5 cm. Higher resolution sampling was conducted within this interval due to the presence of several predominantly terminal Cretaceous palynological taxa range tops. Care was taken to avoid rock reworked due to bioturbation evidenced by the presence of *Planolites* ichnofacies. The geographic locations of the samples are plotted on Fig. 2.1 and their stratigraphic positions are plotted on Figs. 2.2, 2.3 and 2.4. Provenance of float matrices (Appendix 1.B) has been inferred through lithological and palynological assemblage correlation.

2.5.1.2 Preparation

Samples were processed using a standardized palynomorph extraction procedure (e.g., Pospelova et al., 2010). For each of the samples, subsamples of ~ 2 cm³ of matrix were placed in 50 ml polypropylene test tubes. The dry weights of these samples were recorded and averaged ~ 5.4 g. Samples were treated repeatedly with 10 ml of 10% room-temperature hydrochloric acid (HCl) in order to dissolve any carbonates. A single *Lycopodium clavatum* tablet of batch #177745 (18584 ± 1853 spores per tablet, produced at the Department of Geology, University of Lund, Sweden) or batch #2013001 ($27,560 \pm 2643$ spores per tablet, produced at the Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences, Nanjing, China) was added to each sample to enable analysis of palynomorph absolute abundances (e.g., Benninghoff, 1962; Stockmarr, 1971; Mertens et al., 2009b, 2012c).

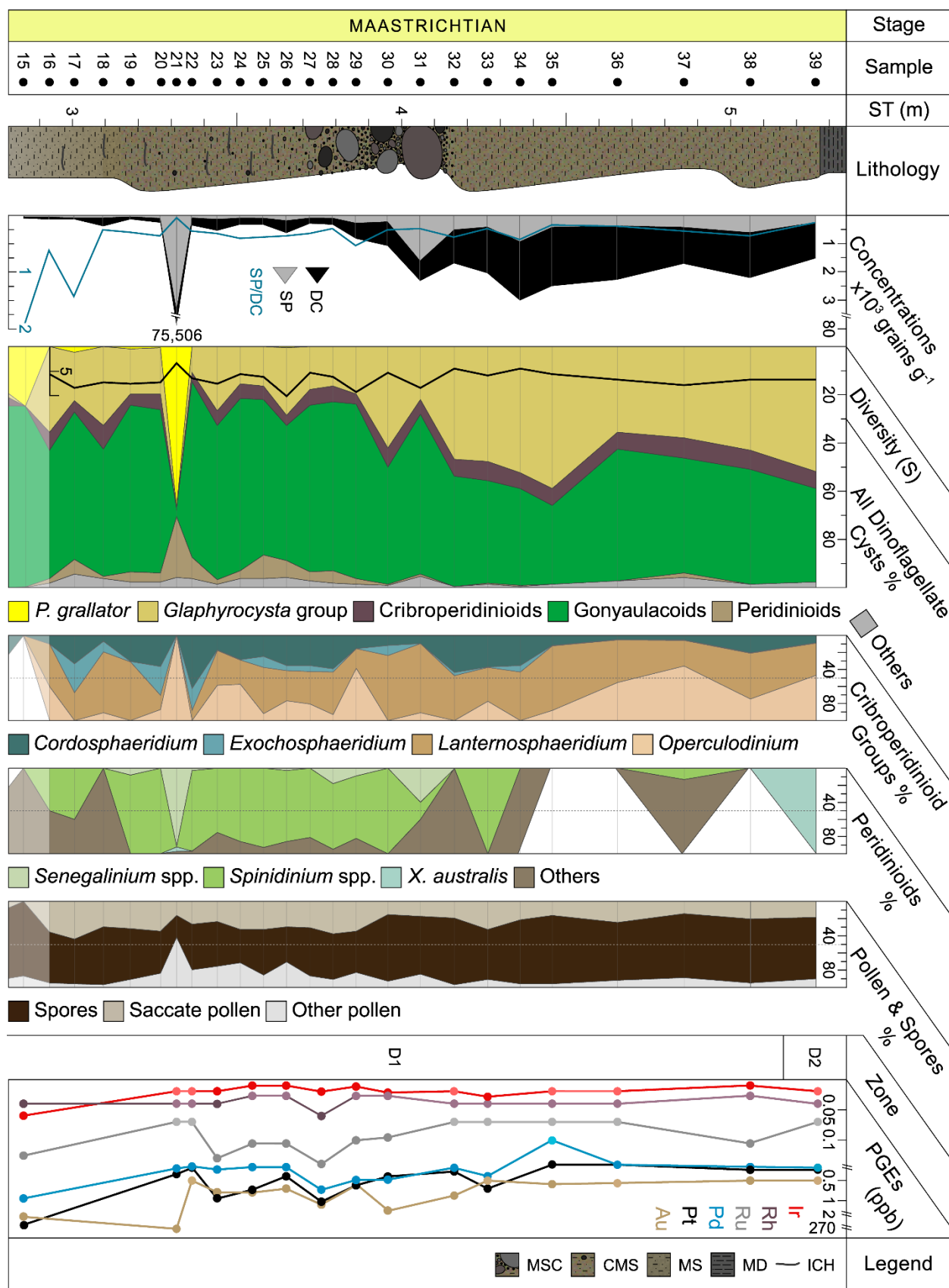


← **Figure 2.2.** Schematic framework and composite measured thickness of the Oyster Bay Formation (Vancouver Island, British Columbia, Canada) from the Lynnwood, Appian Way and Oyster River sections. Plotted abundance curves of selected dinoflagellate cyst groups and species, as well as pollen and spores illustrating fluctuations in assemblage ecology and palynomorph concentrations across the K/Pg boundary interval. Abundance curve opacity denotes data derived from sample counts of <50 dinoflagellate cysts, spores, or pollen grains. Higher resolution sampling interval expanded in Fig. 3, highlighted in red. Dinoflagellate cyst zones and iridium concentrations are indicated to the right. Abbreviations: ST, stratigraphical level above base of section; OR, Oyster River; Ax 1, anticline axis; Ax 2, syncline axis; DC, dinoflagellate cysts; SP, spores and pollen; MF, macrofossils; CN, concretions; MD, mudstone; SM, sandy mudstone; MS, muddy sandstone; SA, sandstone; CG, conglomerate.

Following HCl treatment, the samples were placed in 20 ml of 48% room-temperature hydrofluoric acid (HF) where they were left to sit with daily stirring from ten to twenty-five days depending on the amount of silicate minerals present. Afterward, each sample underwent one round of HCl and two rinses of reverse osmosis water to remove any HF residue before final sieving through 120 μm and 15 μm Nitex nylon mesh to remove remaining particles. The samples underwent up to 1 min of ultrasonic agitation (Mertens et al., 2012c; Price et al., 2016) to dislodge any minute rock particles from organic materials and centrifuging took place at 3600 rpm. Once sieving was completed, residue was mounted in glycerin jelly on microscope slides for bright-field microscopy. Samples were assigned catalogue numbers and are housed within the Paleoenvironmental/Marine Palynology Laboratory, School of Earth and Ocean Sciences, University of Victoria (Victoria, BC, Canada).

2.5.1.3 Counting

Palynomorph identification and counts were conducted at 600x magnification wherein a single specimen was recorded if more than half its structure was intact (operculum notwithstanding), such as a bisaccate pollen grain central body in association with at least one bladder and a trilete spore of at least two-thirds. Foraminiferal organic linings were also counted. Counts exceeding 400 dinoflagellate cysts were reached where possible over a maximum of four slides to obtain optimal relative abundance distributions in high-diversity assemblages, a number targeted in numerous K/Pg boundary studies (e.g., Slimani et al., 2010, 2012, 2016) beyond the



← **Figure 2.3.** Schematic diagram of high-resolution sampling section above the base of the Lynnwood section of the Oyster Bay Formation (Vancouver Island, British Columbia, Canada). Plotted abundance curves of selected dinoflagellate cyst groups and species, as well as pollen and spores illustrating fluctuations in assemblage ecology and palynomorph concentrations. Abundance curve opacity denotes data derived from sample counts of <50 dinoflagellates cysts, spores, or pollen grains. Dinoflagellate cyst zones and platinum group element concentrations are indicated to the right. Abbreviations: ST, stratigraphical level above base of section; DC, dinoflagellate cysts; SP, spores and pollen; MSC, muddy sand conglomerate; CMS, conglomeratic muddy sandstone; MS, muddy sandstone; MD, mudstone; ICH, *Planolites* ichnofacies.

statistically sufficient sample size of 300 cysts as determined for analyses of Quaternary deposits (Mertens et al., 2009b). An average of 420 dinoflagellate cysts were counted across the 71 most productive samples which yielded concentrations of >50 cysts g⁻¹. At least two slides were examined for each sample to account for rare outlying taxa.

Marine palynomorphs were assigned to dinoflagellate cysts and acritarchs at the specific level where possible; all are generally well-preserved. Pollen grains and spores were predominantly assigned to categories based on gross morphology. Grouping of taxa (spp.) was conducted during the counting process where the number of specimens belonging to a genus was extremely limited but hypothetically conducive to specific-level differentiation. Taxa were assigned to a generic or specific *complex* if a given level of identification was possible, yet specimens frequently presented within a plexus of morphological intergradation. *Spiniferites–Nematosphaeropsis* intergrades, which are known to have been produced under laboratory conditions (Rochon et al., 2009), were grouped together.

2.5.1.4 Presentation

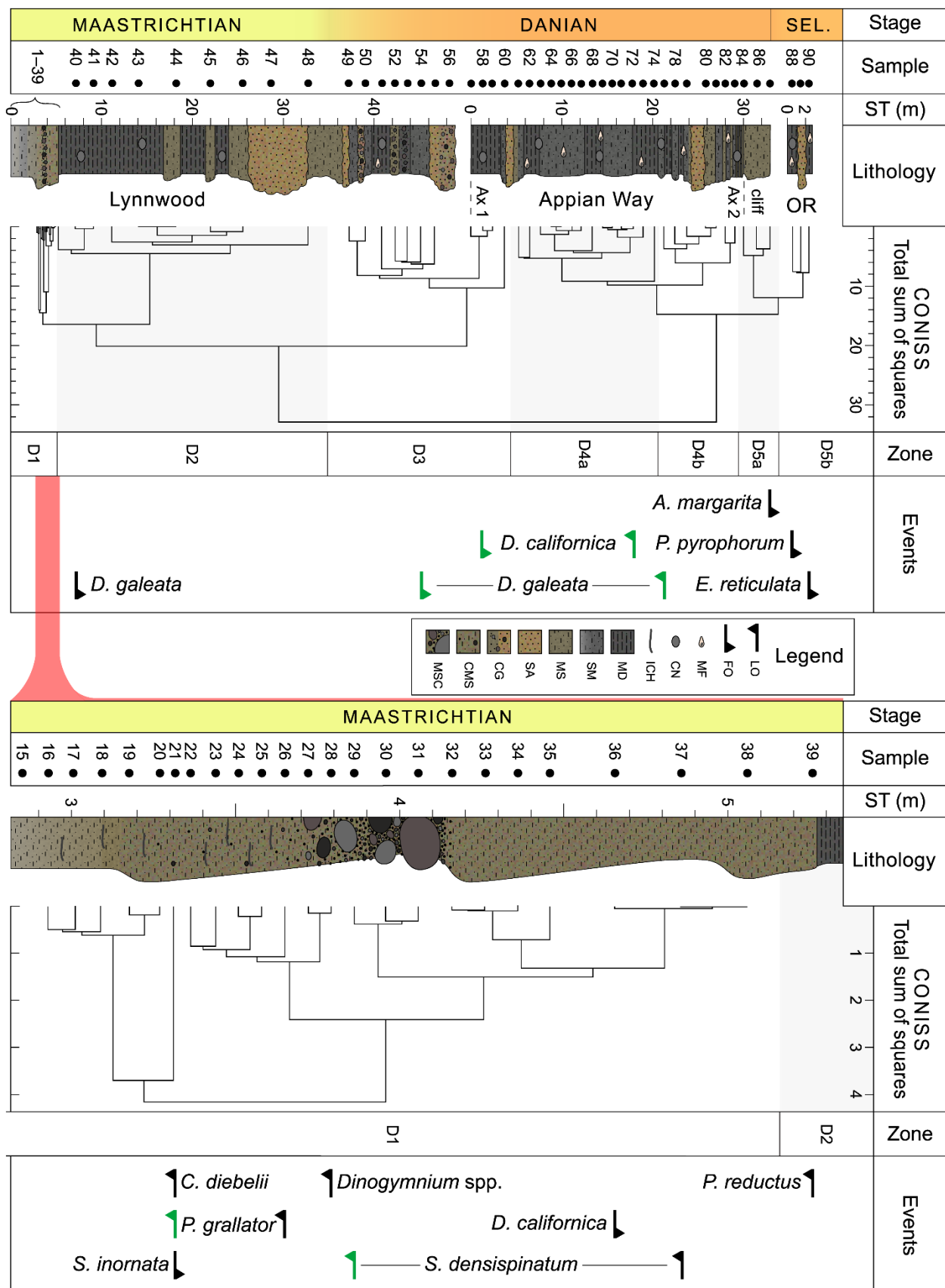
Photomicrographs were taken under 600x or 1000x magnification with a Nikon DS-5M-L1 digital camera system mounted on a Nikon Eclipse 80i transmitted light microscope. For clarity of presentation in microfossil specimen bright-field photomicrographs, extraneous particulate debris were removed from the field of view (Riding and Head, 2018) with a brush tool using Macromedia Fireworks 8 software if the material was not in contact with the specimen ambitus.

Photomicrographs were also taken following epifluorescence analysis which was conducted on selected deflandreoid dinoflagellate cysts for the purpose of establishing primary production capability (e.g., Wood, 1955; Lessard and Swift, 1986; Pospelova and Head, 2002) by exposing them to ultraviolet light for a minimum of 2 min using a Nikon Intensilight C-HGFI precentred fiber illuminator. Terminology relating to classes of relative abundance follow the parameters of Pospelova et al. (2004): present (>0–1%); rare (>1–5%); common (>5–30%); abundant (>30–50%); dominant (>51%).

2.5.2 Statistical analysis

Stratigraphically constrained cluster analysis (CONISS) was performed using Tilia 2.6.1 software (Grimm, 1991–2019) square root transformation (Edwards and Cavalli-Sforza, 1964) and incorporated only those taxa which comprise >1.5% of any assemblage for the purpose of defining dinoflagellate cyst zones. Samples obtained from float matrices were excluded due to imprecision of their stratigraphic positioning. In addition to dinoflagellate cyst taxa richness, species diversity was calculated through obtaining *D* and *H* values using both the Gini-Simpson (Gini, 1912; Simpson, 1949) and Shannon-Wiener (Shannon and Weaver, 1949) indices, respectively. By extension, Shannon-Wiener *H* values were used to ascertain the probable number of equally abundant species (*S*) as a measure of assemblage heterogeneity following the formula $\exp(H) = S$ (Jost, 2006). Results are based on samples from which counts of >50 dinoflagellate cysts were performed as to include samples of sparse concentration at the base of the Lynnwood section.

A literature review of the known geographic locations of selected dinoflagellate cysts, established as K/Pg interval indicator taxa, was conducted for the purpose of ascertaining the extent of their spatial and temporal association. Ten dinoflagellate cyst taxa present in the Oyster Bay Formation were selected based on their known K/Pg boundary constraints or prevalence in proximity to the K/Pg boundary. Occurrence data pertaining to these dinoflagellate cysts were compiled from a total of 683 reports obtained from 349 published studies. Records prior to 2004 were retrieved with the assistance of the PALYNODATA online database (Palynodata Inc. and White, 2008). The records and publications referenced are listed in Appendix 1.C according to species and associated age.



← **Figure 2.4.** CONISS cluster dendrograms, associated dinoflagellate cyst zonation and identified palynological events plotted against the composite measured thickness of the Oyster Bay Formation (Vancouver Island, British Columbia, Canada) from the Lynnwood, Appian Way and Oyster River sections. Green denotes a first or last consistent occurrence event where a species comprises >1.5% of an assemblage. Abbreviations: ST, stratigraphical level above base of section; OR, Oyster River; Ax-1, anticline axis; Ax-2, syncline axis; LO, last occurrence; FO, first occurrence; MF, macrofossils; CN, concretions; ICH, *Planolites* ichnofacies; MD, mudstone; SM, sandy mudstone; MS, muddy sandstone; SA, sandstone; CG, conglomerate; CMS, conglomeratic muddy sandstone; MSC, muddy sand conglomerate.

2.5.3 Geochemical analysis

To assist in constraining the K/Pg boundary within the Lynnwood section, pyrometallurgical analysis of platinum group elements (PGEs) was conducted at the Geoscience Laboratories, Ontario Geological Survey, Ontario Ministry of Energy, Northern Development and Mines, Sudbury, Ontario. Twenty-two samples were powdered to 15 g (<90 µm particle size) before undergoing nickel-sulphide fire assaying. During the assay, samples were fused for 90 min at 1050 °C with sodium carbonate and sodium tetraborate in the presence of nickel and sulphur as to partition the metals from borosilicate slag into the NiS collector. The resulting NiS beads were transferred to Teflon vessels for 37% HCl treatment followed by tellurium coprecipitation of the residue for maximum metal recovery. After coprecipitation, solutions were vacuum filtered and the precipitate subsequently re-dissolved in aqua regia at room-temperature and brought to volume with deionized water. A Perkin-Elmer ELAN 5000 inductively coupled plasma mass spectrometer was then used to ascertain PGE concentrations.

To further refine interpretation of the paleoenvironmental setting, $\delta^{13}\text{C}$ isotopic analysis was performed at the Pacific Centre for Isotopic and Geochemical Research, Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia (Vancouver, BC). Thirty-two samples from the basal Lynnwood section were powdered to 200 mg (<63 µm particle size) for analyses carried out using a Fisons elemental analyzer and a Thermo Finnigan Delta Plus isotope ratio mass spectrometer in continuous flow mode. The measurements were corrected to VPDB based on an average of repeated runs of acetanilide and calibrated against

NBS international standard 19. Full PGE concentrations and isotopic data are provided in Appendix 2.D.

2.6 Results

2.6.1 Palynology

Ten of the 90 samples collected were found to be barren of marine microfossils; these samples (samples 1–3, 5–9, 11, 12) were recovered from the basal muddy sandstones of the Lynnwood section. Terrestrial palynomorphs were observed in all samples. With respect to all organic microfossils, the most productive samples were typically mudstones or those intermixed with finer grained rocks and higher carbonate content. A mélange of vascular plant cuticles, phytoclasts and amorphous organic material was observed regularly. Relative abundances of the major marine and terrestrial constituents are plotted throughout each section, alongside dinoflagellate cyst and pollen and spore concentrations (Figs. 2.2 and 2.3). Notable palynological events throughout each section are plotted in Fig. 2.4. A complete list of all taxa observed in this study is included in Appendix 1.A and accompanied by additional photomicrographs. Palynological counts, concentrations, relative abundances, taxa richness and diversity and are shown in Appendix 1.B.

2.6.1.1 *Dinoflagellate cysts*

Representatives from at least six dinoflagellate cyst families were identified throughout the Oyster Bay Formation (Plates 2.1, 2.2 and 2.3). Beyond those samples that were barren, nine samples in the Lynnwood section yielded <50 dinoflagellate cysts g^{-1} and statistically insignificant counts for relative abundance calculations. In total, at least 57 dinoflagellate cyst genera were found to be present encompassing at least 112 species. Of the productive samples, minimum taxa richness ranges from 11 in the Lynnwood section to 43 at the top of the Oyster River section. The diversity index values for D (0.42) and H (1.16) are lowest at 40.8 m in the Lynnwood section prior to the major assemblage turnover whereas S (~ 3.41) values are lowest at 3.3 m in the

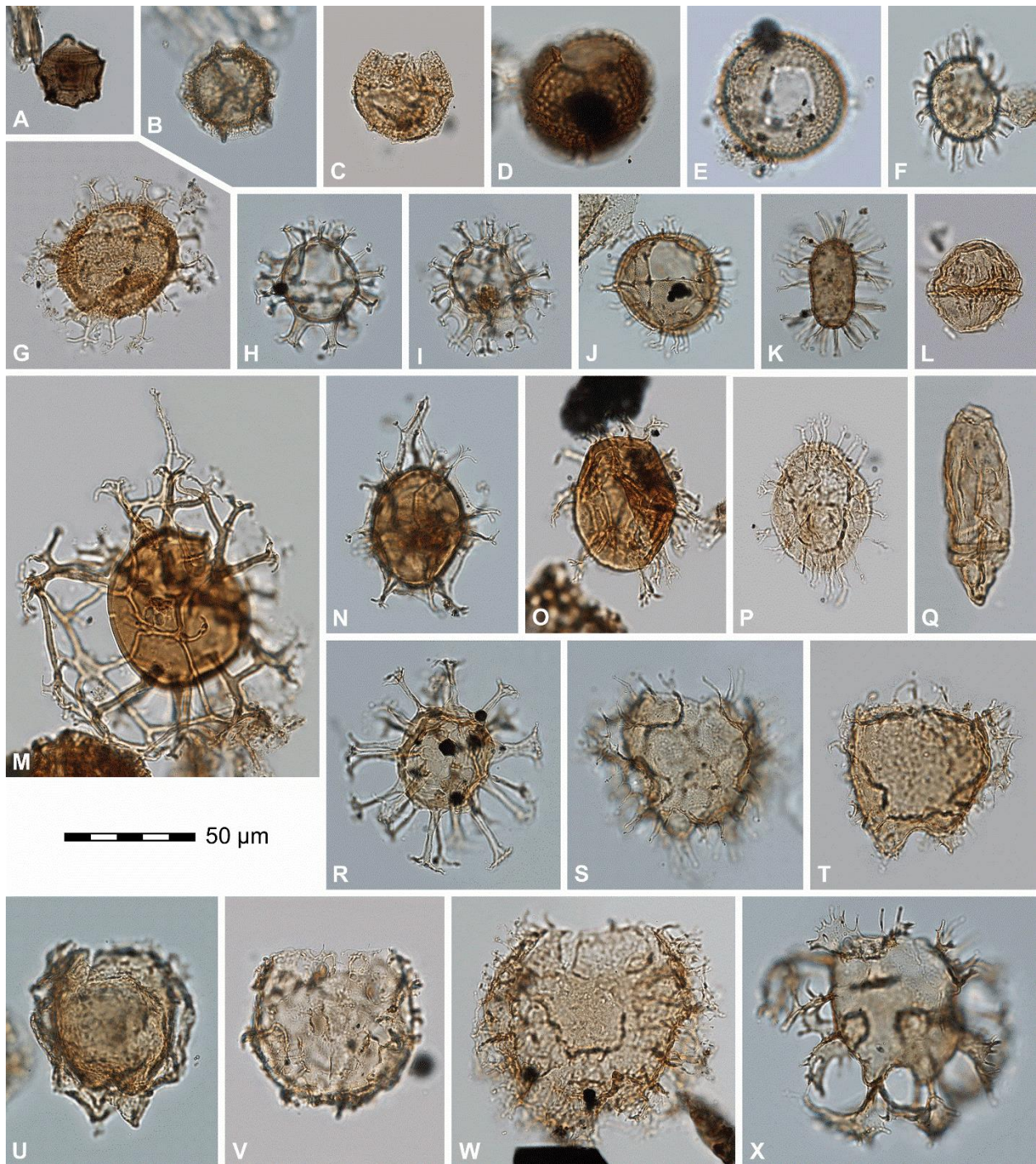


Plate 2.1. Bright-field photomicrographs of representative dinoflagellate cysts. Specimen samples and positions in brackets. Section abbreviations: AW, Appian Way; LN, Lynnwood; OR, Oyster River. **A**, *Glyphanodinium facetum* (90, OR 2.3 m). **B**, *Fibradinium annetorpense* (62, AW 6.6 m). **C**, *Alisocysta margarita* (90, OR 2.3 m). **D**, *Eisenackia reticulata* (90, OR 2.3 m). **E**, *Xenicodinium delicatum* (77, AW ~20–22 m). **F**, *Kiokansium* sp. of Nøhr-Hansen (1994) (21, LN 3.3 m). **G**, *Achomosphaera* cf. *sagena*

(26, 3.7 m). **H**, *Spiniferites* cf. *hyperacanthus* of Jan du Chêne (1987) (62, AW 6.6 m). **I**, *Spiniferites* cf. *mirabilis* of Jan du Chêne (1987) (75, AW ~20–22 m). **J**, *Hafniasphaera septata* (21, LN 3.3 m). **K**, *Tanyosphaeridium xanthiopyxides* (90, OR 2.3 m). **L**, *Dinogymnium cretaceum* (26, LN 3.7 m). **M**, *Cannosphaeropsis franciscana* (21, LN 3.3 m). **N**, *Spiniferella cornuta* cf. subsp. *cornuta* (74, AW 20 m). **O**, *Spiniferites pseudofurcatus* (51, LN 40.8 m). **P**, cyst of *Spiniferites* complex (53, LN 43.5 m). **Q**, *Dinogymnium digitus* (22, LN 3.4 m). **R**, *Hystrichosphaeridium tubiferum* (21, LN 3.3 m). **S, T**, *Palynodinium grallator* (21, LN 3.3 m). **U**, *Canningia glomerata* (21, LN 3.3 m). **V**, *Cyclonephelium compactum* (54, LN 45 m). **W**, *Glaphyrocysta divaricata* (35, LN 4.5 m). **X**, *Areoligera volata* (62, AW 6.6 m).

Lynnwood section and 23.4 m in the Appian Way section. The indices *D* (0.88), *H* (2.61) and *S* (13.60) find their highest values at 3.6 m in the Appian Way section.

Areoligeraceans are attributable to seven genera: *Areoligera*, *Canningia*, *Cyclonephelium*, *Glaphyrocysta*, *Palynodinium*, *Senoniasphaera* and *Tenua*. *Palynodinium grallator* presents one of the most striking areoligeracean acmes at 67% in being constrained to within ~0.1 m at 3.3 m in the Lynnwood section, punctuating an interval where the species otherwise remains below 2.5% (Fig. 2.3). The lowest diversity index values throughout the succession are owing to instances of areoligeracean dominance. Species belonging to *Areoligera*, *Glaphyrocysta* and *Cyclonephelium* are also the most consistently well represented ranging from 10.7 to 84.8% throughout the Lynnwood section, 11.7 to 68.3% in the Appian Way section and 2.5 to 62.9% in the Oyster River section. Examples of *Canningia*, *Senoniasphaera* and *Tenua* are known only from a small number of specimens (Appendix 1.B, Table 1).

The peridinioids are the most diverse category consisting of the nine deflandreoid genera *Andalusiella*, *Cerodinium*, *Deflandrea*, *Ginginodinium*, *Palaeocystodinium*, *Senegalinium*, *Spinidinium*, *Vozzhennikovia* and *Xenikoon* as well as seven other peridinioid genera including *Diconodinium*, *Laciniadinium*, *Lejeunecysta*, *Maduradinium*, *Octodinium*, *Palaeoperidinium* and *Phelodinium*. Peridinioid occurrence is sparse in the Lynnwood section with *Spinidinium* spp. peaking at <10.0% in the basal 4.0 m (Fig. 2.3). A gradual shift in peridinioid abundance begins to take place in the lowermost Appian Way section and is fully realized in dramatic fashion at 6.6 m by a pulse of *Senegalinium* spp. (16.9%) and *Xenikoon australis* (19.9%). Species of

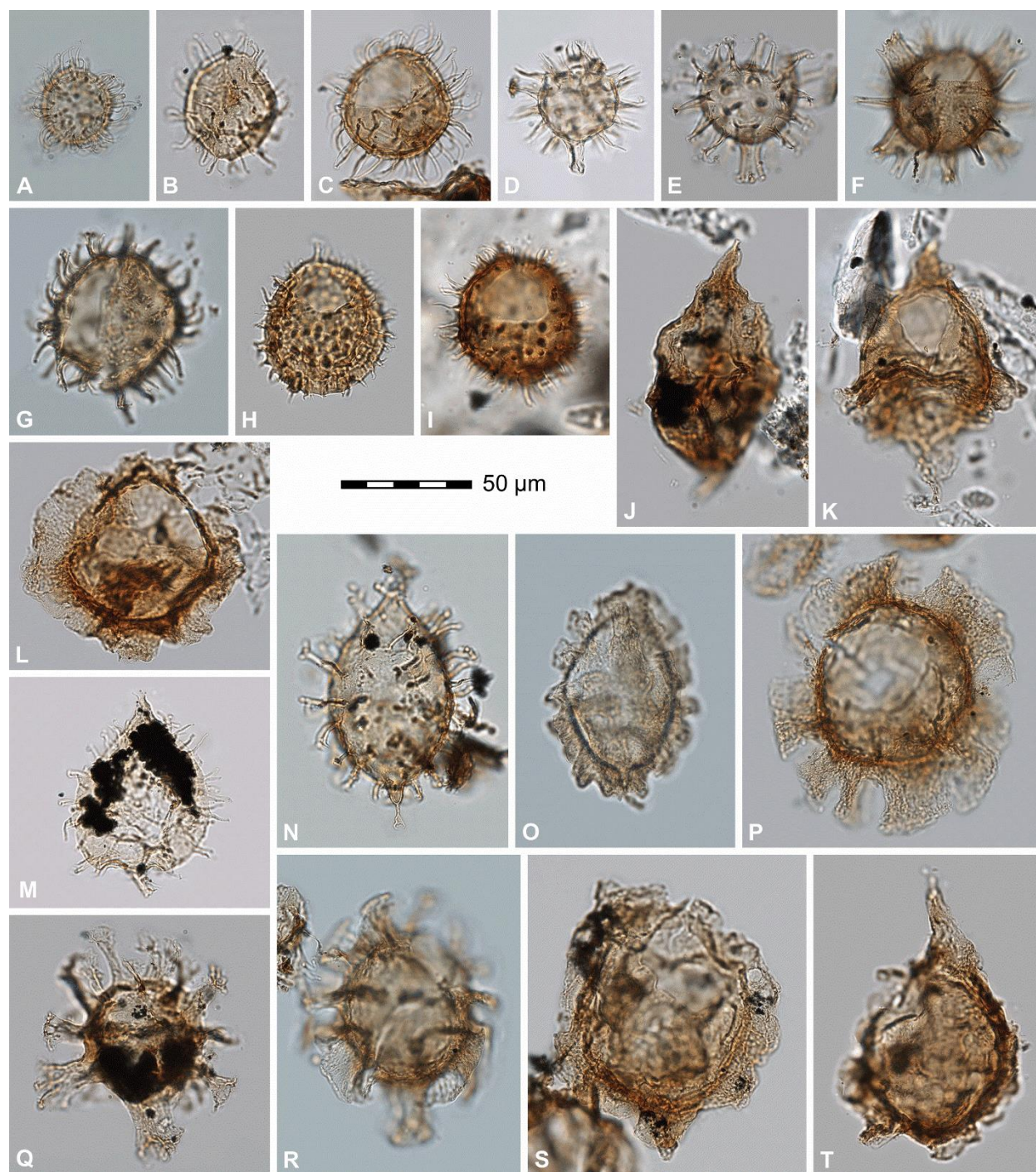


Plate 2.2. Bright-field photomicrographs of representative cribroperidinioid dinoflagellate cysts.

Specimen samples and positions in brackets. Section abbreviations: AW, Appian Way; LN, Lynnwood; OR, Oyster River. **A**, *Operculodinium minutum* (90, OR 2.3 m). **B**, *Operculodinium taiwanianum* (49, LN 37.4 m). **C**, *Operculodinium* cf. *eirikianum* (76, AW 20.9 m). **D**, *Diphyes colligerum* (75, AW ~20–22 m). **E**, *Diphyes digitum* (80, AW 25.8 m). **F**, *Florentinia ferox* (90, OR 2.3 m). **G**, *Exochosphaeridium bifidum* (62, AW 6.6 m). **H**, **I**, *Exochosphaeridium phragmites* (69, AW 15.1 m; 81, AW 27 m). **J**,

Kenleyia pachycerata (41, LN 9 m). **K**, *Kenleyia lophophora* (45, LN 21.8 m). **L**, *Muratodinium fimbriatum* (20, LN 3.27 m). **M**, *Ifecysta lappacea* (50, LN 39 m). **N**, *Ifecysta fusiforma* (60, AW 3.6 m). **O**, *Ifecysta pachyderma* (62, AW 6.6 m). **P**, *Cordosphaeridium fibrospinosum* (21, LN 3.3 m). **Q**, *Cordosphaeridium inodes* (49, LN 37.4 m). **R**, *Danea californica* (62, AW 6.6 m). **S**, *Lanternosphaeridium lanosum* (32, LN 4.2 m). **T**, *Turbiosphaera magnifica* (35, LN 4.5 m).

Senegalinium and *Ginginodinium*, shown to autofluoresce under ultraviolet light (Appendix 1.A, S Figs. 1A–C), later see increases leading to dominance in a number of assemblages higher in the Appian Way and Oyster River sections. All other exclusively heterotrophic peridinioid taxa, those which do not autofluoresce, rarely surpass 4.0% (Appendix 1.B, Table 2).

The cribroperidinioids exhibit the second highest diversity with the subfamily being represented predominantly by the genera *Apteodinium*, *Cordosphaeridium*, *Exochosphaeridium*, *Kenleyia*, *Lanternosphaeridium*, *Muratodinium* and *Operculodinium* and to a lesser extent species belonging to *Danea*, *Diphyes*, *Florentinia*, *Hystrichokolpoma*, *Ifecysta* and *Turbiosphaera* which rarely exceed 5.0% (Appendix 1.B, Table 2). In the Lynnwood section, cribroperidinioid abundance ranges from 0.2 to 35.5%. In tandem with the onset of the deflandreoid pulse in the lower Appian Way section, *Exochosphaeridium phragmites* emerges to dominate the cribroperidinioid assemblages throughout much of the remaining succession, comprising 16.3% of all dinoflagellate cysts on average until a marked decline in the Oyster River beds (Fig. 2.2).

Gonyaulacoids range from 3.0 to 71.9% in the Lynnwood section, 6.0 to 21.7% in the Appian Way section and 3.9 to 10.1% in the Oyster River section (Figs. 2.2, 2.3). Throughout the entire succession, *Achomosphaera* (0.0 to 7.5%), *Cannosphaeropsis* (0.0 to 5.8%) and chiefly *Spiniferites* (1.9 to 67.4%) taxa encompass the vast majority of the subfamily constituents with members of *Hafniasphaera*, *Impagidinium*, *Kiokansium*, *Nematosphaeropsis*, *Pterodinium* and *Spiniferella* comprising no more than 4.0% of any assemblage combined. Rare *Spiniferites*–*Nematosphaeropsis* intergrades, presumed to be *Spiniferites* complex outliers, were only observed below 4.4 m in the Lynnwood section and account for a maximum of 1.6% of any assemblage. All other gonyaulacaceans, including species of *Leptodinium*, *Stephodinium*? and *Xenicodinium*, never exceed 5.5% as a whole (Appendix 1.B, Table 2).

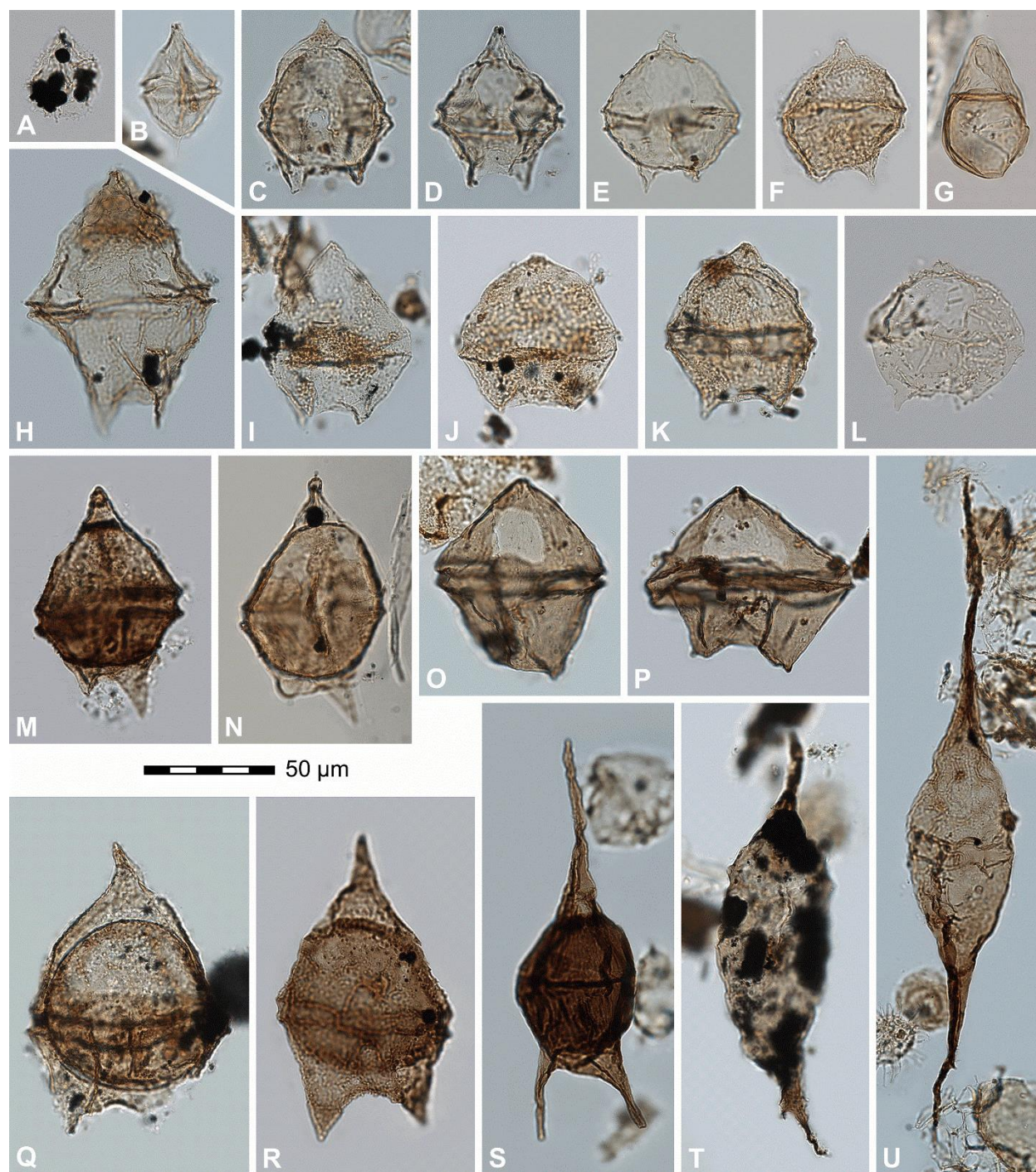


Plate 2.3. Bright-field photomicrographs of representative peridiniinean dinoflagellate cysts. Specimen sample and position in brackets. Section abbreviations: AW, Appian Way; LN, Lynnwood; OR, Oyster River. **A**, *Vozzhennikovia* cf. *minus* (59, AW 2.3 m). **B**, *Laciniadinium arcticum* (62, AW 6.6 m). **C**, **D**, *Senegalinium dilwynense* (C, 74, AW 20 m; D, 75, AW ~20–22 m). **E**, *Senegalinium obscurum* (90, OR 2.3 m). **F**, *Senegalinium microgranulatum* (21, LN 3.3 m). **G**, *Xenikoon australis* (81, AW 20 m). **H**, *Palaeoperidinium pyrophorum* (88, OR 0.6 m). **I**, *Maduradinium* sp. (75, AW ~20–22 m). **J**,

Maduradinium pentagonum (74, AW 20 m). **K**, *Spinidinium bellum* (74, AW 20 m). **L**, *Spinidinium densispinatum* (26, LN 3.7 m). **M**, **N**, *Ginginodinium* cf. sp. A of Steeman et al. (2020) (**M**, echinate var., 85, AW ~30–31.5 m; **N**, granulate var., 90, OR 2.3 m). **O**, *Lejeunecysta* cf. *hyalina* (74, AW 20 m). **P**, *Lejeunecysta lata* (74, AW 20 m). **Q**, *Deflandrea oebisfeldensis* (85, AW ~30–31.5 m). **R**, *Deflandrea galeata* (67, AW 12.4 m). **S**, *Cerodinium diebelii* (21, LN 3.3 m). **T**, *Andalusiella gabonensis*, (77, AW ~20–22 m). **U**, *Palaeocystodinium golzowense* (21, LN 3.3 m).

Goniodomaceans include taxa assigned to *Alisocysta*, *Eisenackia*, *Eocladopyxis*? and *Hystrichosphaeridium*. With the exception of *Hystrichosphaeridium tubiferum*, which reaches up to 14.0% in the upper Lynnwood section (Fig. 2.2), members of the family are never recorded above 2.3%. Likewise, other minor constituents belonging to outlying families such as *Glyphanodinium* and *Fibradinium* of the Cladopyxiaceae and *Dinogymnium* of the Ptychodiscaceae, are similarly rare, along with taxa of uncertain familial placement, which represent <1.3% of all dinoflagellate cysts, on average (Appendix 1.B, Table 2).

2.6.1.2 Other marine microfossils and palynomorphs

An array of acritarchs, algal cysts and palynomorphs *incertae sedis* are present in the Oyster Bay Formation (Plate 2.4, figs. A–L; Appendix 1.A, SFig. 3). These predominantly marine constituents of presumed non-flagellate affinity occur seldomly in assemblages prior to the Oyster River section, save for periodic elevated concentrations of *Baltisphaeridium* cf. *crameri*, *Micrhystridium fragile* and *Paralecaniella indentata* in the Appian Way section. Members of other acritarch genera such as *Pterospermopsis* are sparse throughout, with *Cymatiosphaera* sp., *Fromea* sp., non-descript chorate acritarchs and several ambiguous coronate and kalyptate palynomorphs all see increased specimen recovery in the Oyster River section (Appendix 1.B, Table 1). Foraminiferal organic linings (Plate 2.4, figs. K, L), of uniserial, biserial and planispiral morphology, increase in prevalence moving up in the formation. Of those recorded in statistical counts, 14 were observed in the Lynnwood section, 44 in the Appian Way section and eight within the Oyster River section. Pyrite endocasts of a single silicoflagellate skeleton and three



Plate 2.4. Bright-field photomicrographs of selected marine and terrestrial microfossils. Specimen samples and positions in brackets. Section abbreviations: AW, Appian Way; LN, Lynnwood; OR, Oyster River. **A**, *Corbisema hastata globulata*, silicoflagellate pyrite endocast (77, AW ~20–22 m). **B**, *Medlinia weissei*, diatom pyrite endocast (77, AW ~20–22 m). **C–E**, scolecodont maxillae (C, 77, AW ~20–22 m; D, 74, AW 20 m; E, 27, LN 3.7 m). **F**, *Michhystridium fragile* (75, AW ~20–22 m). **G**, *Paralecaniella indentata* (90, OR 2.3 m). **H**, *Baltisphaeridium* cf. *crameri* (85, AW ~30–31.5 m). **I**, *Pterospermopsis*

danica (86, AW 31.5 m). **J**, *Pterospermopsis aureolata* (90, OR 2.3 m). **K, L**, foraminiferal organic linings (**K**, 90, OR 2.3 m; **L**, 85, AW ~30–31.5 m). **M**, *Ephedripites* sp. (37, LN 4.9 m). **N**, *Parviprojectus reductus* (25, LN 3.6 m). **O**, *Podocarpidites* sp. A (60, AW 3.6 m). **P**, *Momipites* sp. (22, LN 3.4 m). **Q**, *Tricolpites* sp. cf. pollen of *Gynoplatananthus oysterbayensis* (88, OR 0.6 m). **R**, *Tschudypollis thalmannii*, (88, OR 0.6 m). **S**, *Tschudypollis?* sp. (74, AW 20 m). **T**, *Propylipollis* sp. (85, AW ~30–31.5 m). **U**, *Echinatisporis* sp. (34, LN 4.4 m). **V**, *Trilites* sp. (39, LN 5.3 m). **W**, *Osmundacidites* sp. (26, LN 3.7 m). **X**, *Margocolporites* sp. (90, OR 2.3 m). **Y**, *Concavissimisporites* sp. (88, OR 0.6 m). **Z**, *Lycopodiacidites* sp. (30, LN 4 m). **AA**, *Trilobosporites* sp. A (78, AW 21.8 m). **BB**, *Deltoidospora* sp. (41, LN 9 m).

diatom frustuels were recovered (Plate 2.4, figs. A, B). Scolecodont jaw apparatuses (Plate 2.4, figs. C–E) are also exceedingly rare with only six observed in total.

2.6.1.3 Terrestrial palynomorphs

A comprehensive taxonomic survey of the pollen grains and spores present throughout the succession was not conducted in this study, although the most productive samples yielded diverse terrestrial assemblages (Plate 2.4, figs. M–BB). Miospores generally comprise the majority of the terrestrial constituents, with representatives from at least eleven palynogenera ranging from 25.7 to 86.4%. Most belong to fern families and include species of *Concavissimisporites*, *Deltoidospora*, *Echinatisporis*, *Gleicheniidites*, *Laevigatosporites*, *Lycopodiacidites*, *Ornamentifera*, *Osmundacidites*, *Trilites* and *Trilobosporites*. Other outlying forms, such as *Stereisporites*, indicate the presence of mosses. Saccate pollen accounts for 13.6 to 74.3% of the assemblages and specimens are largely assignable to *Alisporites*, *Piceapollenites* and *Podocarpidites*. Conversely, colpate, colporate and porate pollen constitute at most 15.4% of all terrestrial constituents. However, these angiosperm grains approach comparable diversity in being attributable to at least eight palynogenera, among them *Chenopodipollis?*, *Ephedripites*, *Margocolporites*, *Momipites*, *Propylipollis*, *Tricolpites*, *Tricolporites*, *Triporopollenites* and *Tschudypollis*. Triprojectates are one of the rarest forms of angiosperm pollen with most grains having been recovered from the basal Lynnwood section and include those of the exclusively late Maastrichtian species *Parviprojectus reductus* (Plate 2.4, fig. N) (e.g., Braman and Sweet, 2012; Braman, 2013, 2018).

2.6.2 Dinoflagellate cyst zones

2.6.2.1 Dinoflagellate Cyst Zone D1 (0 to ~5.2 m in the Lynnwood section)

Zone D1 has the highest abundances of *Spiniferites* spp. (3.0 to 71.9%; avg. 54.0%) and *Lanternosphaeridium lanosum* (avg. 2.3%) as well as the highest spore/pollen ratio (avg. 59.5%) (Figs. 2.2 and 2.3). Diversity index values for the dinoflagellate cyst assemblages are the second lowest on average with $D = 0.74$, $H = 1.87$, $S = 6.71$ and minimum taxa richness at 23. The interval contains the last occurrence (LO) of *Spinidinium densispinatum* (4.9 m) as well as those of the latest Maastrichtian indicators *Dinogymnium cretaceum* (3.8 m) and *Palynodinium grallator* (3.7 m). The first inconsistent occurrence (FIO) of *Danea californica* (4.7 m) and the first occurrence (FO) of *Senoniasphaera inornata* (3.3 m) are also present (Fig. 2.4).

2.6.2.2 Dinoflagellate Cyst Zone D2 (~5.2 to 35.1 m in the Lynnwood section)

Zone D2 presents the highest consistent abundances of members of the *Glaphyrocysta* group (42.0 to 83.0%; avg. 61.3%), the *Kenleyia* complex (*K. lophophora* and *K. pachycerata* intergrades, avg. 5.6%) and *Muratodinium fimbriatum* (avg. 5.8%) as well as the lowest dinoflagellate cyst concentrations (avg. 2,921 g⁻¹) (Fig. 2.2). This zone exhibits the greatest dinoflagellate cyst homogeneity with the overall lowest diversity index values on average wherein $D = 0.76$, $H = 1.86$, $S = 6.42$ and minimum taxa richness is 16. The base of Zone D2 is approximately concurrent with the LO of the latest Maastrichtian triprojectate pollen species *Parviprojectus reductus* (5.3 m) which is situated below the FIO of *Deflandrea galeata* at ~7 m in the Lynnwood section (Fig. 2.4).

2.6.2.3 Dinoflagellate Cyst Zone D3 (~35.1 to 48.2 m in the Lynnwood section; 0 to ~4.3 m in the Appian Way section)

Zone D3 presents the highest abundances of *Hystrichosphaeridium tubiferum* (avg. 7.5%), *Cannosphaeropsis franciscana* (avg. 3.3%), *Cordosphaeridium* spp. (avg. 7.8%), *Danea californica* (avg. 1.3%) and *Ifecysta* spp. (avg. 2.8%). This zone is further characterized by successively alternating peaks of the *Areoligera volata* complex and members of the *Glaphyrocysta* group (Fig. 2.2; section 2.6.3). Among terrestrial constituents, Zone D3 contains

the highest abundance of saccate pollen (42.2 to 62.4%; avg. 54.0%) and the lowest spore/pollen ratio (avg. 37.5%). The dinoflagellate cyst diversity is marked by the lowest Gini-Simpson (D) values averaging 0.72 alongside the third highest values for the other indices wherein $H = 1.94$, $S = 7.69$ and minimum taxa richness averages 24. The top of Zone D3 is also defined by the LO and highest abundance of *Vozzhennikovia* cf. *minus* at ~4.3 m in the Appian Way section. Based on the first consistent occurrence (FCO) of *Danea californica* at 1.3 m in the Appian Way section (Fig. 2.4, Sample 58) following a major phytoplankton paleoecological turnover, this zone encompasses the center point of the K/Pg boundary interval with the boundary itself approximated at the D2–D3 zonal interface.

2.6.2.4 Dinoflagellate Cyst Zone D4 (~4.3 to 29.5 m in the Appian Way section)

Zone D4 is defined by the highest consistent abundances of the *Areoligera volata* complex (avg. 36.9%), *Exochosphaeridium phragmites* (avg. 17.5%) and heterotrophic peridinioid taxa (avg. 1.8%) as well as a high spore/pollen ratio (avg. 56.4%) (Fig. 2.2). The dinoflagellate cyst diversity is the second highest on average wherein $D = 0.78$, $H = 2.07$, $S = 8.30$ and minimum taxa richness is 32. This zone also yields the highest abundances of marine and terrestrial macrofossils.

Subzone D4a (~4.3 to 20.5 m) is marked by the highest dinoflagellate cyst concentrations (avg. 15,542 cysts g⁻¹) (Fig. 2.2). Specimens belonging to the *A. volata* complex (avg. 33.3%), *E. phragmites* (avg. 17.4%) and *Senegalinium* spp. (avg. 18.2%) are common. The last consistent occurrence (LCO) of *Danea californica* is present at 18.0 m (Fig. 2.4). The range of *Apteodinium* cf. *fallax* (6.6 to ~20.5–22 m) corresponds approximately to the depth of this subzone.

Subzone D4b (~20.5 to 29.5 m) is characterized by the highest abundances of the rare taxa *Ifecysta pachyderma* (avg. 0.8%) and *Operculodinium* spp. (avg. 2.4%). *Xenikoon australis* also has its highest abundance (avg. 4.8%) proportionate to the depth of the subzone (Fig. 2.2). Representatives of the *A. volata* complex (avg. 44.1%) and *E. phragmites* (avg. 17.7%) are common assemblage constituents while *Senegalinium* spp. (avg. 2.7%) are generally rare. The base of this subzone is approximately equivalent with the LCO of *Deflandrea galeata* at ~20.9 m (Fig. 2.4).

2.6.2.5 Dinoflagellate Cyst Zone D5 (~29.5 to 33.0 m in the Appian Way section; 0 to 2.3 m in the Oyster River section)

The base of Zone D5 is approximately concurrent with the FO of *Alisocysta margarita* at the base of the sandstone cliff (~30 to 31.5 m) in the Appian Way section, demarcating the transition to the earliest Selandian (Fig. 2.4). The dinoflagellate cyst diversity is the highest on average in this zone wherein $D = 0.81$, $H = 2.17$, $S = 9.03$ and minimum taxa richness is 33.

Subzone D5a (~29.5 m to the top of the measured Appian Way section) is distinguished by the highest abundance of *Ginginodinium* cf. sp. A of Steeman et al. (2020) (avg. 30.1%) with the *Areoligera volata* complex (avg. 20.8%) and *Exochosphaeridium phragmites* (avg. 14.5%) being common (Fig. 2.2).

Subzone D5b (encompassing the Oyster River section) has its base defined by the FO of *Areoligera circumsenonensis* at 0 m in the Oyster River section (Fig. 2.4). The subzone is further characterized by the highest abundance of *Senegalinium* spp. (avg. 33.6%) as well as the presence of *Eisenackia reticulata* and *Palaeoperidinium pyrophorum*. Subzone D5b also exhibits the highest diversity of nondescript palynomorphs and pollen. The *A. volata* complex (avg. 23.2%) is common while *E. phragmites* (avg. 3.9%) is rare.

2.6.3 Dinoflagellate cyst ecogroups

The practice of establishing generic-level groups of non-analogue taxa with similar forms as to extrapolate paleoenvironmental signals from palynological datasets was employed (Frieling and Sluijs, 2018) as has become conventional in studies of Late Cretaceous–early Paleogene assemblages (e.g., Schiøler et al., 1997; Sluijs and Brinkhuis, 2009; Slimani et al., 2010; Shcherbinina et al., 2016; Guler et al., 2019; Vellekoop et al., 2019; Chakir et al., 2020). Given the considerable diversity of the dinoflagellate cysts within the Oyster Bay Formation, the following nine ecogroups were able to be recognized: (1) *Areoligera* spp. which is almost entirely comprised of the *A. volata* complex; (2) the *Glaphyrocysta* group which includes all species of *Glaphyrocysta* and *Cyclonephelium*; (3) the *Cordosphaeridium* group, (4) *Exochosphaeridium* spp. and (5) the *Lanternosphaeridium* group among the fibrous cribroperidinioids; (6) the *Operculodinium* group among the non-fibrous cribroperidinioids; (7)

the *Spiniferites* group; and lastly, (8) *Senegalinium* spp. and (9) *Spinidinium* spp. among the deflandreoid peridinioids.

The *Cordosphaeridium* group consists of the genera *Apteodinium*, *Cordosphaeridium*, *Kenleyia* and *Turbiosphaera* which present only polar ectophragmal projections whereas the *Lanternosphaeridium* group is comprised of the genera *Danea*, *Ifecysta*, *Lanternosphaeridium* and *Muratodinium* which present polar endophragmal projections. *Lanternosphaeridium* is grouped with the Cribroperidinioideae herein based on gross morphology. The *Operculodinium* group includes the genera *Diphyes* and *Operculodinium* after Powell et al. (1996) along with *Florentinia* and *Hystrichokolpoma*. The *Spiniferites* group is an amalgamation of all species belonging to *Achomosphaera*, *Cannosphaeropsis*, *Hafniasphaera*, *Nematosphaeropsis*, *Spiniferella* and *Spiniferites*.

2.6.4 Relative dating

The palynological assemblages of the Oyster Bay Formation indicate that the unit spans ~4.5 to 5 myr, with an age extending from the latest Maastrichtian to the earliest Selandian. The latest Maastrichtian range tops of *Dinogymnium* spp., *Palynodinium grallator* and *Parviprojectus reductus* all occur below 6.0 m in the Lynnwood section as does the range base of *Senoniasphaera inornata*. Although the FCO of the Danian index species *Danea californica* appears at 1.3 m in the Appian Way section (Fig. 2.4, Sample 58), the beginning of the herein interpreted post-Cretaceous paleoecological turnover occurs between Sample 48 (32.7 m) and Sample 49 (37.4 m) in the upper Lynnwood section (UTM Grid Reference 343215E, 5531860N, Zone 10U; WGS84), constituting the nexus of the K/Pg boundary interval. Key dinoflagellate cysts in the Oyster Bay Formation with global ranges in proximity to the K/Pg interval include: *Danea californica*, *Deflandrea galeata*, *Eisenackia reticulata*, *Fibradinium annetropense*, *Palynodinium grallator*, *Senegalinium dilwynense*, *S. microgranulatum*, *S. obscurum*, *Senoniasphaera inornata* and *Xenikoon australis* among others. The distribution of all known autochthonous records of the aforementioned species has been plotted for occurrences of late Maastrichtian and Danian age (Figs. 2.5 and 2.6). Taken as a lot, 86.6% of all autochthonous reports of these ten taxa are constrained to within the late Maastrichtian to Danian

geochronological interval. Of the 683 records obtained, twenty-seven were excluded from the calculation; thirteen due to a lack of chronostratigraphic precision, eight which were presumed by their authors to have been reworked taxa and seven which were determined to be misidentifications when photomicrographs were presented (Appendix 1.C). The FO of *Alisocysta margarita* is used to demarcate the Danian–Selandian boundary, which is approximated at the top of the Appian Way section at the base of the sandstone cliff (UTM Grid Reference 343640E, 5531065N, Zone 10U; WGS84).

2.6.5 Geochemistry

Platinum group elemental analyses did not reveal any discernable anomalies (Appendix 2.D, Table 3). Concentrations of gold (<0.6 to 270 ppb; avg. ~13.2 ppb), iridium (0.01 to 0.06 ppb; avg. ~0.02 ppb), platinum (0.22 to 2.21 ppb; avg. 0.55 ppb) palladium (<0.20 to 0.95 ppb; avg. ~0.44 ppb), rhodium (<0.04 to 0.06 ppb; avg. ~0.05 ppb) and ruthenium (<0.08 to 0.18 ppb; avg. ~0.10 ppb) were found to fall within the accepted range for the upper continental crust (e.g., Racki et al., 2011; Park et al., 2012) (Figs. 2.2 and 2.3). Isotopic analyses of organic carbon from the muddy sandstones to muddy sand conglomerate of the basal Lynnwood section yielded significantly negative $\delta^{13}\text{C}_{\text{org}}$ values ranging from -25.50 to -27.53‰ VPDB (avg. -26.36‰) (Appendix 2.D, Table 1, SFig. 1).

2.7 Discussion

2.7.1 Age of the Oyster Bay Formation

An elevation in platinum group element (PGE) levels has long been the principle geochemical signature used for demarcating the K/Pg boundary which has been linked to both deep mantle and cosmogenic sources associated with the end-Cretaceous mass extinction event (e.g., Schulte et al., 2010; Goderis et al., 2013; Chalapathi Rao et al., 2014). Detection of this signal is

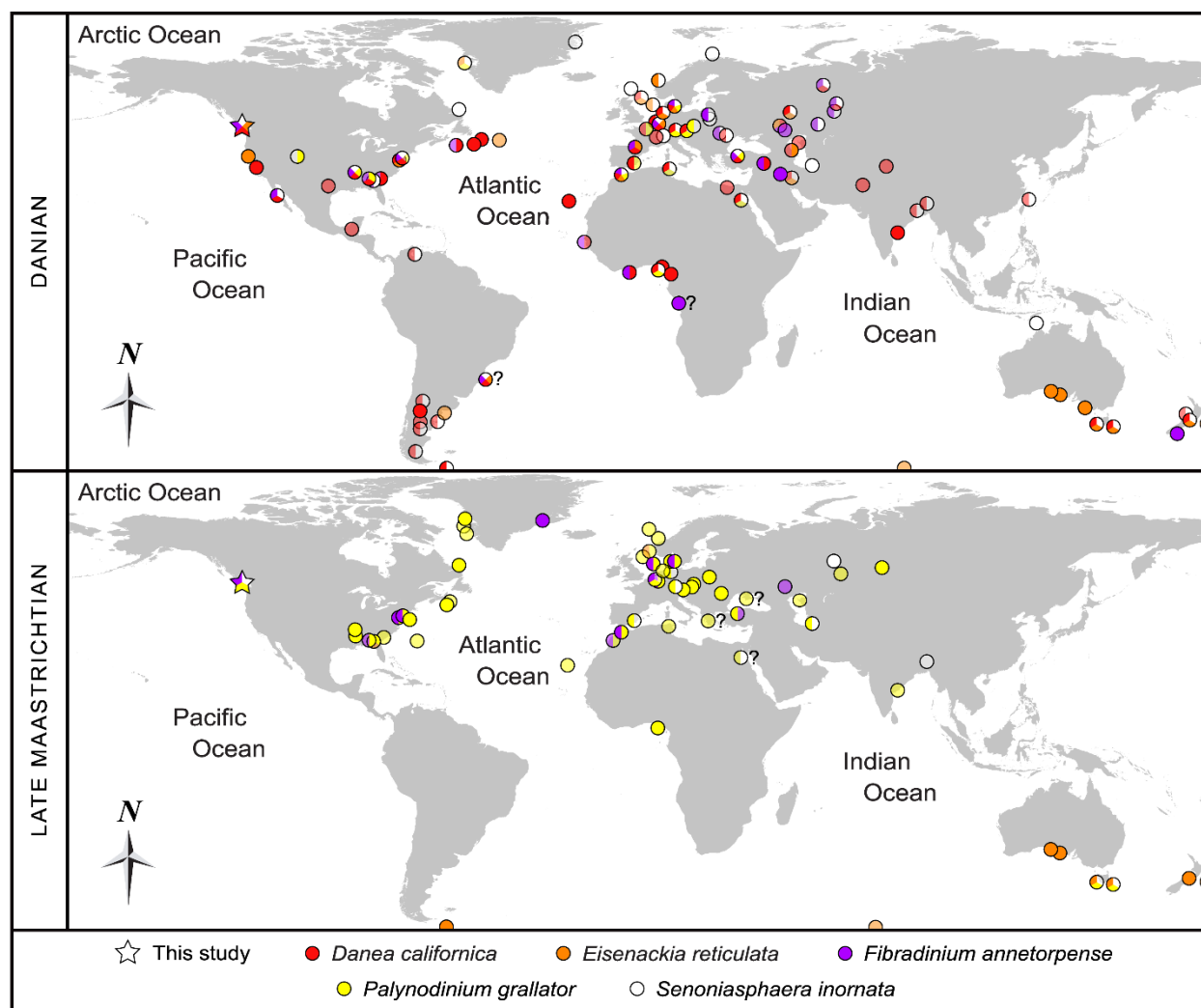


Figure 2.5. Global distribution of selected dinoflagellate cyst K/Pg boundary interval indicator taxa present within the Oyster Bay Formation, Vancouver Island, British Columbia, Canada, as reported from strata of late Maastrichtian and Danian age. Colour opacity denotes non-illustrated records. Star indicates location of study area.

typically achieved in temporally condensed successions where it is preserved within a thin clay layer among fine-grained sedimentary rocks, resulting from low-energy paleoenvironmental conditions optimal for the concentration and retention of these heavy metal proxies (e.g., Sawlowicz, 1993; Racki et al., 2011; Esmeray-Senlet et al., 2017). The lack of an apparent peak in proximity to the boundary in the present study, namely the absence of an iridium anomaly, is not surprising. The limited resolution of our spot sampling notwithstanding, a likely high sedimentation rate as well as coincidence with the deposition of a massive sandstone deposit at

the convergence of zones D2 and D3 are major factors that would contribute to the dilution of a PGE acme without question. As a result, relative age determinations have been accomplished using micropaleontological biostratigraphic markers, primarily dinoflagellate cysts.

The extinction of *Dinogymnium* spp. and *Palynodinium grallator* are widely utilized events marking the top of the Cretaceous (e.g., Stover et al., 1996; Williams et al., 2004), although records of potential short-term survival of *Dinogymnium* spp. into the earliest Paleocene are known in Europe (Brinkhuis and Zachariasse, 1988; Mohamed et al., 2013; Açikalin et al., 2015) and North Africa (Brinkhuis and Schiøler, 1996; Vellekoop et al., 2015; Chakir et al., 2020), with other post-Cretaceous rare occurrences having been attributed to reworking immediately above the K/Pg boundary in these and other Northern Hemisphere regions (Slimani et al., 2010; Oboh-Ikuenobe et al., 2012; Mohamed and Wagreich, 2013; Dastas et al., 2014; Mahboub et al., 2019). It bears consideration that a widespread abundance peak of *P. grallator*, just prior to the K/Pg boundary, may be the most telling dinoflagellate cyst signal and indicator for the terminal Cretaceous at mid- to high latitudes in the Northern Hemisphere (e.g., Hansen, 1977; Hultberg, 1986; Schiøler and Wilson, 1993; Habib et al., 1996; M. Vieira pers. comm. to SMSM in 2018; Vellekoop et al., 2019) as opposed to its last appearance datum. Such an acme was found at 3.3 m in the Lynnwood section (Sample 21) and it is characterized by aggregate masses of cysts dominating the assemblage comparable to what have recently been reported from coeval strata in New Jersey (Vellekoop et al., 2019). Similar to observations of *Dinogymnium* spp., instances of *P. grallator* persisting into the earliest Danian have been documented in eastern North America (e.g., Moshkovitz and Habib, 1993; Habib et al., 1996; Dastas et al., 2014; Vellekoop et al., 2016, 2019) Greenland (Nøhr-Hansen and Dam, 1997; Dam et al., 1998), Europe (e.g., Brinkhuis et al., 1998; Bubik et al., 2002; Gedl, 2004; Egger and Mohamed, 2010; Mohamed et al., 2012, 2013; Açikalin et al., 2015; FitzPatrick et al., 2017) and North Africa (Oloto, 1990; Brinkhuis et al., 1998; Slimani et al., 2010; Soliman and Slimani, 2019; Jbari et al., 2020) within close proximity to the K/Pg boundary. Danian occurrences attributed to reworking were reported from the Netherlands (Brinkhuis and Schiøler, 1996) as well as New Jersey and Maryland (Landman et al., 2004a, 2004b).

Perhaps the foremost cosmopolitan index taxon used as a tool for establishing K/Pg boundary proximity is *Danea californica* (e.g., Moshkovitz and Habib, 1993; Stover et al., 1996; Williams et al., 2004; Molina et al., 2006; FitzPatrick et al., 2017), stemming from early work which

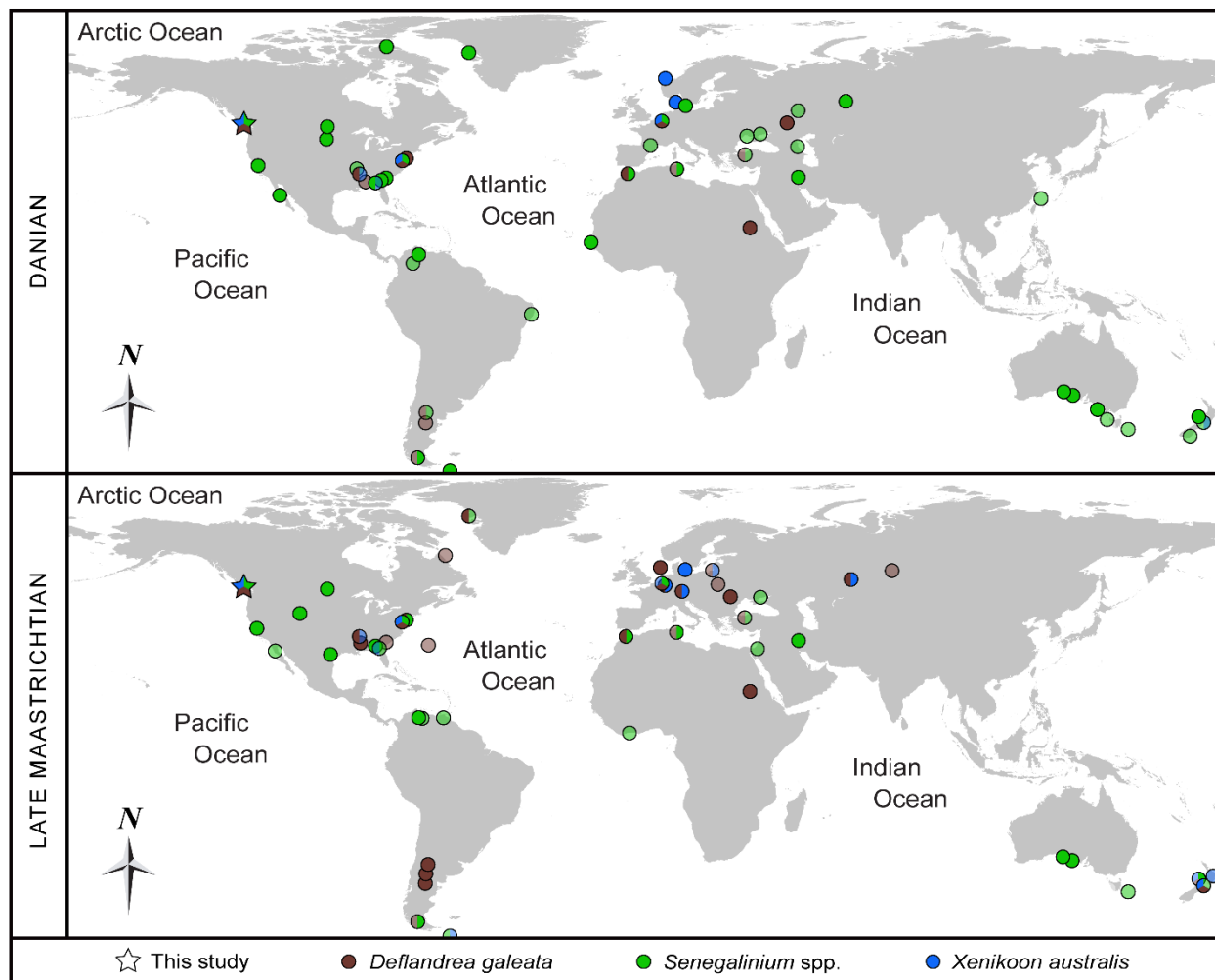


Figure 2.6. Global distribution of selected deflandreoid dinoflagellate cyst taxa present within the Oyster Bay Formation, Vancouver Island, British Columbia, Canada, as reported from strata of late Maastrichtian and Danian age. *Senegalinium* spp. comprises *S. dilwynense*, *S. microgranulatum* and *S. obscurum*. Colour opacity denotes non-illustrated records. Star indicates location of study area.

recognized the species as a Danian zonal indicator reflected in its namesake (e.g., Hansen, 1977; Brinkhuis and Zachariasse, 1988; Brinkhuis and Leereveld, 1988). Forms intergradational with *Cordosphaeridium fibrospinosum* could pose a challenge in the diagnosis of *D. californica* (e.g., Dastas et al., 2014; Vellekoop et al., 2017; Scasso et al., 2020). In order to establish a reliable position for the FO of *D. californica* s.s., we observe the FCO of the species as the definitive indicator of basal Danian strata; a measure adopted for some taxa in other coeval biostratigraphic studies (e.g., Crouch et al., 2014; Jbari et al., 2020). Apart from a few isolated intergrades above

4.6 m in the Lynnwood section, *D. californica* sees its FCO in the Appian Way section at 1.3 m and LCO at 18.0 m (Fig. 2.4). This position is entirely compatible with the maximum age of 63.1 ± 1.0 Ma obtained from detrital zircons sampled from the sandstone layer ~24.0 m above this mark (Haggart et al., in prep; J. W. Haggart pers. comm. to SMSM in 2018) in light of the International Commission on Stratigraphy recognizing the K/Pg boundary at 66.0 Ma (Cohen et al., 2013). *Danea californica* persists into the earliest Selandian of the Oyster River section in Sample 89; the highest range top for the species as reported from other regions of the Northern Hemisphere (e.g., Powell et al., 1992a; Morton et al., 1988; Fensome et al., 2009). The FO of *Senoniasphaera inornata* near the base of the Lynnwood section is somewhat unusual in that the taxon is typically an indicator for the earliest Danian (e.g., Brinkhuis and Schiøler, 1996; Miller et al., 2010; Slimani et al., 2011). However, late Maastrichtian records are known from Europe (de Coninck and Smit, 1982; Köthe, 1991; Marheinecke, 1992; Smit and Brinkhuis, 1996), Asia (Vasilyeva, 2003; Garg et al., 2006; Ghourchaei et al., 2015), the southern Pacific (Schellenberg et al., 2004) and possibly North Africa (Soliman and Slimani, 2019). It is important to note that *Danea californica*, *Dinogymnium* spp., *P. grallator* and *S. inornata* have all been recognized from the Global Stratotype Section and Point (GSSP) for the base of the Danian Stage near El Kef, Tunisia (e.g., Molina et al., 2006; M’Hamdi et al., 2015; Vellekoop et al., 2015).

Several peridinioid taxa present in the studied cyst assemblages have broad geographic ranges and are also useful for determining age constraints. *Deflandrea galeata* is a well-established marker for upper Maastrichtian–Danian strata (e.g., Landman et al., 2007; Slimani et al., 2011; Vellekoop et al., 2015) and has been employed as an index taxon in a multitude of late Maastrichtian biozonation schemes (e.g., Wilson, 1974; Kirsch, 1991; Slimani, 2001). Species often found in association, such as *Senegalinium dilwynense* and *S. obscurum*, are most frequently reported in studies of Paleocene strata but are not constrained to the series (e.g., Crouch and Brinkhuis, 2005; Quattrocchio, 2009; Hollis et al., 2017). Similarly, *S. microgranulatum* finds its most prevalent records from late Maastrichtian–Danian-aged strata (e.g., Nøhr-Hansen and Dam, 1997; Slimani et al., 2010; Wan et al., 2014) with fewer exceptions extending into the late Paleocene–early Eocene (Norris, 1997; Rabbani et al., 2015); one datum is potentially as recent as the earliest Oligocene (Sung Zhichen et al., 1978). *Xenikoon australis* is well known from Maastrichtian–Danian successions (e.g., Laird et al., 2003; Surlyk et al., 2013; Vieira et al., 2017), although much of the literature considers its occurrence in the

Southern Hemisphere, where the species was first established as a zonal indicator for the early Campanian of Australia (e.g., Evans, 1966; Helby et al., 1987). The range of *Cerodinium diebelii* extends into the Selandian, but the species is most commonly reported from Cretaceous assemblages of late Campanian–late Maastrichtian age (e.g., Fensome et al., 2008; Nøhr-Hansen et al., 2011) and is often found in association with higher abundances of *Palaeocystodinium golzowense* (e.g., Oboh-Ikuenobe et al., 2012; Lebedeva et al., 2017). *Spinidinium densispinatum* and *S. echinoideum* have been recognized as existing on a plexus of intergradation largely contingent on the length of spinous ornament (e.g., Heilmann-Clausen, 1985; Steeman et al., 2020). Taken together, both taxa are common in studies of the Upper Cretaceous–lower Paleocene rocks. These species are also present within the Campanian Northumberland Formation on Hornby Island, BC (McLachlan et al., 2018) with *S. echinoideum* having been used as a zonal index for the Campanian–Maastrichtian interval of the western North Pacific (Kurita and Obuse, 1997). At other mid- to high latitudes, *S. densispinatum* is frequently reported from rocks of Danian–early Selandian age (e.g., Thomsen and Heilmann-Clausen, 1985; Fensome et al., 2008), with rare occurrences possibly ranging into the Thanetian in the Southern Hemisphere (e.g., Bowman et al., 2016; Steeman et al., 2020).

Major dinoflagellate cyst age indicators present in the Oyster Bay Formation also include the outlying goniodomid species *Alisocysta margarita*, *Eisenackia reticulata* and *Fibradinium annetropense*. *Alisocysta margarita* is largely constrained to the early Selandian–middle Thanetian and has therefore been an important tool in the biostratigraphic zonation of Paleocene successions (e.g., Powell et al., 1996; Williams et al., 2004; Bijl et al., 2021), although isolated occurrences have been placed within the Danian (e.g., Slimani et al., 2016). The composition of uppermost dinoflagellate cyst subzone D5b from the Oyster River bears greatest similarity to Selandian assemblages at higher latitudes, which have also been defined in part by the combined presence of *A. margarita*, *Areoligera circumsenonensis* and *Palaeoperidinium pyrophorum* (e.g., Heilmann-Clausen, 1985; Iakovleva et al., 2001; Nagy et al., 2004). *Eisenackia reticulata* holds a global distribution with greatest utility for determining strata of Danian age in the Northern Hemisphere (e.g., Luterbacher et al., 2004; Williams et al., 2004) with only two FO instances in upper Maastrichtian strata (Firth, 1987; Bell et al., 1990). In the Southern Hemisphere, *E. reticulata* is generally less chronostratigraphically constrained, with a number of late Maastrichtian reports (e.g., Askin, 1988; Schellenberg et al., 2004) and a range top in the early

Thanetian (Naeher et al., 2019). Hollis et al. (2017) even observed the species as part of a broader intergeneric *reticulata-margarita* complex. *Fibradinium annetropense* has a somewhat longer range with the bulk of its reports hailing from upper Maastrichtian–Danian rock packages (e.g., M’Hamdi et al., 2013; Dastas et al., 2014; Slimani et al., 2016). A host of other dinoflagellate cysts such as *Apteodinium fallax*, *Areoligera volata* and *Xenicodinium delicatum* are less common in the literature but most widely recognized from Upper Cretaceous intervals and strata of Danian age (e.g., Slimani et al., 2016; Țabără and Slimani, 2017; Țabără et al., 2017).

There is a notable absence of a number of K/Pg boundary indicator taxa of use in other regions, such as *Disphaerogena carposphaeropsis* (e.g., Slimani et al., 2010; Larina et al., 2016; Guler et al., 2019), *Carpateella cornuta* (e.g., Willumsen, 2012; Slimani and Toufiq, 2013; Guédé et al., 2014) and *Thalassiphora pelagica* (e.g., Brinkhuis and Schiøler, 1996; Schiøler et al., 1997; Vellekoop et al., 2016). Peridinioid taxa belonging to the genus *Manumiella* recognized for their acmes demarcating the latest Maastrichtian in both hemispheres (e.g., Habib and Saeedi 2007; Thorn et al., 2009; Slimani et al., 2010, 2016; Scasso et al., 2020) are also conspicuously absent from the Oyster Bay Formation, despite being abundant at numerous locations elsewhere in the circum-Pacific region including California (Drugg, 1967), New Zealand (e.g., Wilson, 1984) and Australia (e.g., Helby et al., 1987). The ancestral wetzelielloid *Apectodinium*, which emerged in the earliest Selandian (Williams et al., 2015) and dominated assemblages in the late Paleocene (e.g., Bujak and Brinkhuis, 1998; Prasad et al., 2006), does not occur in the highest beds of the succession exposed on the Oyster River; this may be owing to extremely low abundances or diachroneity with its first appearance datum at low latitudes (e.g., Brinkhuis et al., 1994; Garg et al., 2006).

A shift from fern spore dominance to gymnosperm pollen dominance marks the K/Pg interval as has been reported from the North American Western Interior (e.g., Nichols and Johnson, 2008; Bercovici et al., 2009; Prauss, 2009; Bercovici and Vellekoop, 2017) and New Zealand (Vajda et al., 2001; Vajda and Raine, 2003), with a similar trend observed in Japan (Saito et al., 1986). A number of typically Cretaceous spores and pollen grains, including those of *Parviprojectus reductus*, may have been reworked as were reported in one of four samples from the Appian Way beds examined by Sweet (2005). Mixed assemblages of both autochthonous and reworked terrestrial palynomorphs would not be unexpected, especially following an influx of

terrigenous material up-section. However, the exquisite dinoflagellate cyst preservation quality, low thermal maturation and magnitude of concentrations overwhelmingly favours autochthonous placement of the marine components within the Oyster Bay Formation. Visible dinoflagellate cyst degradation as to potentially suggest reworking has only been observed in isolated specimens of *Canningia reticulata* recovered from the basal conglomeratic muddy sandstones of the Lynnwood section (Appendix 1.B, Table 1).

2.7.2 Nanaimo Group affinity

The sandstone to conglomerate Gabriola Formation exposed in the southern Gulf Islands is the uppermost stratal unit of the Nanaimo Group succession and is regarded to be of Maastrichtian age (e.g., Mustard, 1994; Katnick and Mustard, 2003; Mustard et al., 2003; Haggart et al., 2011; Bain and Hubbard, 2016; Matthews et al., 2017; Haggart and Graham, 2018) with decidedly late Maastrichtian paleomagnetic (Raub et al., 1998; Enkin et al., 2001; Ward et al., 2012) and detrital zircon-derived U-Pb (Mustard et al., 1995) signatures. Muller and Jeletzky (1970) had considered the Gabriola Formation to be older than the upper Paleocene–middle Eocene Chuckanut Formation but nevertheless, possibly extending into the lower Tertiary. Correlation between the Gabriola Formation and the Chuckanut Formation was later suggested by Vance (1975), based on lithology whilst advocating for palynological analyses to assist in resolving the age. Preliminary analyses of terrestrial palynological assemblages were later carried out by Rouse (pers. comm. in Mustard, 1994), the results of which suggested an early Paleocene age for the uppermost Gabriola Formation as inferred from samples recovered from Gabriola and Hornby islands. Sweet (2005) reported terrestrial palynomorphs from the coastal exposures of the Oyster Bay Formation at the Appian Way locality as bearing close affinity with those collected from Hornby Island exposures of the Gabriola Formation (Rouse et al., 1970; Sweet and Mustard, 2003), further reinforcing probable stratal association.

Nanaimo Group outcrops geographically closest to those of the Oyster Bay Formation on Vancouver Island belong to rocks of the Santonian–Campanian Haslam and Cedar District formations. An extensive Upper Cretaceous succession is exposed at Shelter Point, 1 km south-east of the Campbell River municipal boundary and 1.9 km north of the Lynnwood section. Previous reports have assigned the Shelter Point strata to various regional units such as the Spray

(Richards, 1975), Northumberland (Mustard, 1994), Denman (Cathyl-Bickford and Hoffmann, 1998) and Oyster Bay (Ludvigsen and Beard, 1994, 1998; England and Bustin, 1998) formations. However, Shelter Point is now understood to belong to the Cedar District Formation and is of early-late Campanian age based on molluscan fossils (Ward, 1978; Ward et al., 2012) and magnetostratigraphic correlation with strata exposed along the western coast of Denman Island in the Georgia Strait (Enkin et al., 2001; Ward et al., 2012). Mudstones of the Haslam Formation also crop out along the banks of the Oyster River 1.5 km upstream and to the east of the Oyster Bay Formation exposures at the terminus of Lorna Lane. Dated as late Santonian–early Campanian in age (e.g., Haggart and Graham, 2018; Coutts et al., 2020), beds of the Haslam Formation unconformably overlie the massive sandstones of the Comox Formation described by Muller and Jeletzky (1970) at higher elevations further upstream. The position of these Upper Cretaceous units in relation to the Oyster Bay Formation strata indicate the presence of significant localized gaps in the Nanaimo Group succession likely owing to faulting and depositional hiatuses near the periphery of the Nanaimo Basin. Tectonism would have been a factor in subsequent broad-scale movement of these terrains, but in the absence of plutonic bodies in close proximity to these beds as evidenced by the low thermal maturation of the indigenous palynomorphs.

2.7.3 Paleobiogeography and climatic influence

The palynological assemblages from the Oyster Bay Formation make for an intriguing case study with regard to provincialism and the impact of global climatic transition spanning the end of the Cretaceous–early Paleocene. From a paleobotanical perspective, the presence of triprojectate pollen grains establish a clear connection with mainland North America consistent with a position along the margin of the *Aquilapollenites* phytogeoprovince (e.g., Srivastava, 1981; Sweet and Braman, 2001; Vajda and Bercovici, 2014). With respect to marine palynomorphs, the dinoflagellate cysts illustrate circumstances of confluence between a variety of groups with well-defined latitudinal preferences reflecting global temperature gradients or climate zones (Brinkhuis et al., 1998; Slimani et al., 2010; Chakir et al., 2020), as has been extensively documented in recent and modern cyst assemblages (e.g., Mudie and Harland, 1996; Zonneveld et al., 2013). Lentin and Williams (1980) designated three suites of Late Cretaceous

peridinioid genera that can be classified as corresponding to latitudinal gradients; constituents within the Oyster Bay Formation include *Andalusiella*, *Cerodinium*, *Lejenuecysta* and *Senegalinium* of the tropical to subtropical ‘Malloy suite’, *Spinidinium* of the warm-temperate ‘Williams suite’ and *Diconodinium* and *Laciniadinium* of the boreal ‘McIntyre suite’. A comparable convergence of taxa across the K/Pg interval is seen from the inner neritic strata of the Brazos River area, Texas (Prauss, 2009).

It is generally accepted that late Maastrichtian time was characterized by a period of higher mean paleotemperatures relative to the early Maastrichtian, likely tied to a heightened phase of Deccan volcanism in approach to the terminal Cretaceous (e.g., Olsson et al., 2002; Schoene et al., 2015; Barnett et al., 2018). However, due to a paucity of temporal resolution, consensus is lacking as to the duration of the shift toward cooler conditions immediately preceding the abrupt ‘impact winter’ cooling phase which propelled the mass extinction event and lasted decades to millennia (e.g., Galeotti et al., 2004; Vellekoop et al., 2016; Woelders et al., 2017).

Paleothermometry drawing from foraminiferal $\delta^{18}\text{O}$ and Mg/Ca values, combined with those derived from TEX₈₆ organic geochemistry across the New Jersey Coastal Plain, indicate that the ensuing greenhouse conditions resulted in a ~3 to 7 °C increase in sea-surface paleotemperatures (SST) over ~350 kyr prior to a ~1 to 3 °C cooling interval during the last ~50 kyr of the Cretaceous (e.g., Woelders et al., 2018; Vellekoop et al., 2019). These findings contrast with $\delta^{18}\text{O}$ records from the North Pacific Shatzky Rise which suggest that a cooling of up to ~2 °C had begun to impact SST at least 200 kyr before the K/Pg boundary (Liangquan Li and Keller, 1999), with a rise in SST peaking at ~3 °C some 600 kyr after the event (Zachos et al., 1989). This interpretation is consistent with peak warming in the latest Maastrichtian >150 kyr prior to the Danian stage, as shown by Woelders et al. (2017) from sites in South America and the southern mid-Atlantic that is also in general agreement with the findings of other studies (e.g., Olsson et al., 2002; Thibault and Husson, 2016). In their work on the K/Pg interval at Stevns Klint, Denmark, Hart et al. (2004) note that $\delta^{18}\text{O}$ values could be influenced by an influx of isotopically lighter fresh water skewing toward a warmer SST signal as observed in the Danish neritic shelf deposits. This would not be a factor impacting data derived from a pelagic setting.

Several authors have surmised that elevated *Palynodinium grallator* abundance is potentially influenced by SST fluctuation and increased thermal stratification (Brinkhuis et al., 1998; Vellekoop et al., 2015, 2019). Brinkhuis et al. (1998) reported a *P. grallator* FO immediately

above the K/Pg boundary iridium layer at the basal Danian GSSP near El Kef, Tunisia, indicative of high latitude favourability giving way to southerly migration following the short-lived post-Cretaceous cooling phase (Zachos et al., 1989); the brief Danian appearance of the species would be a phenomenon observed in the nearby sections at Elles (Vellekoop et al., 2015) and Ouled Haddou, Morocco (Slimani and Toufiq, 2013). However, Vellekoop et al. (2019) assert that this hypothesis stems from *P. grallator* recovery bias in the boreal realm and that resolving the discrepancy between the aforementioned North African occurrences and major cyst increases elsewhere, coinciding with sediments laid down during the phase of late Maastrichtian warming (e.g., Machalski et al., 2016; Nøhr-Hansen et al., 2016), necessitates that SST not be an exclusive factor accounting for conditions preferential to the species.

Additionally, increased relative abundances of *Senegalinium* spp., members of a predominately subtropical genus at this time, have been observed reaching a peak in Danian strata in proximity to the K/Pg boundary throughout the Northern Hemisphere (Drugg, 1967; Brinkhuis and Zachariasse, 1988; Eshet et al., 1992; Nøhr-Hansen and Dam, 1997; Slimani et al., 2010; Guédé et al., 2014; M'Hamdi et al., 2015) and across a range of southern latitudes from South America (Vellekoop et al., 2017; Woelders et al., 2017; Guler et al., 2019) to Antarctica (Elliot et al., 1994; Askin and Jacobson, 1996; Bowman et al., 2012, 2016; Scasso et al., 2020). It is probable that warmer conditions were more favourable to these taxa (Woelders et al., 2017) lending to their proliferation at higher northern and southern latitudes over the longer term following the K/Pg event, as exemplified by Arctic and Antarctic assemblages near the Paleocene–Eocene Thermal Maximum (e.g., Sluijs et al., 2008; Barke et al., 2012). The subsequent period of elevated SST in the early Danian appears to coincide with the return of *Senegalinium* spp. abundance up-section at Appian Way, taxa which had also experienced heightened prevalence in association with *Palynodinium grallator* in the basal Lynnwood section. This correlation can be seen most vividly in Sample 21 and is inconsistent with the assemblages from New Jersey examined by Vellekoop et al. (2019), which led to the implication of *P. grallator* abundance as a function of productivity in warmer stratified waters, as opposed to influence from freshwater incursion. Furthermore, the decline of warm-temperate *Spinidinium* spp. within Zone D1 may also be indicative of the onset of SST cooling and/or diminished availability of nutrients (cf. Vellekoop et al., 2019). Similarly, the decrease of *Spiniferites* spp. in Zone D2 likely indicates some upper water column instability and/or lower nutrient availability

during a period of transition (Pospelova et al., 2018). It is therefore conceivable that the stratigraphic expanse between the peak abundances of *P. grallator*, *Senegalinium* spp. and *Spinidinium* spp. and the K/Pg boundary turnover in the Lynnwood section may be due to a combination of factors involving a latest Maastrichtian drop in SST and water column stratification, as well as a decrease in community benefit from nutrient-rich brackish waters.

Andalusiella gabonensis, *Ifecysta fusiforma*, *I. heterospinosa* and *I. pachyderma* are tropical species of notable West African affinity (e.g., Oboh-Ikuenobe et al., 1998; Antolinez-Delgado and Oboh-Ikuenobe, 2007; Awad and Oboh-Ikuenobe, 2016; Oboh-Ikuenobe et al., 2017; Steeman et al., 2020). The presence of these species in the Oyster Bay Formation lends support not only to the premise of warming surface waters into the earliest Danian, but also to the presence of an East-West transatlantic surface current. Such currents have been posited to have existed as major vectors during Late Cretaceous time (e.g., Gordon, 1973; Soudry et al., 2006). It is most likely that one developed in conjunction with a Caribbean corridor, as indicated by the distribution of ammonite faunas and dinoflagellate cyst assemblages in the eastern North Pacific (McLachlan and Haggart, 2018; McLachlan et al., 2018), consistent with the tectonic evolution of the region (e.g., Pindell, 1994; Pindell and Kennan, 2009). During the Maastrichtian, a transatlantic current would have driven waters westward directly from a region of inferred high primary productivity in the Moroccan upwelling belt (Alsenz et al., 2013). A case now exists for persistence of this regime into the early Paleocene. Similar dinoflagellate cyst assemblages in Baja California (Helenes and Téllez-Duarte, 2002) and the Southern Hemisphere have provided evidence of coeval ocean surface circulation from the equatorial Atlantic through the Caribbean and along the eastern coast of South America (Guler et al., 2019) while countercurrents along the western coast of North America, as interpreted based on foraminiferal records (Sliter, 1968, 1972, 1973), would have transported tropical taxa to higher latitudes. Our results support these dinoflagellate cysts as reflective of shifts in global climate and subject to prevailing systems driving the mixing of interregional water masses.

2.7.4 Paleoenvironmental reconstruction

Intervals near the base and top of the Lynnwood section are characterized by interbedded conglomeratic muddy sandstone to sand conglomerate likely attributable to episodic changes in

coastal sediment delivery. A major regression during the latest Maastrichtian global cooling phase (e.g., Pardo et al., 1996; Falkowski et al., 2004; Habib and Saeedi, 2007) sees probable correlation with alternating coarse- and fine-grained beds toward a massive sandstone interval in the upper Lynnwood section as a facies change indicative of shoreline progradation. Haq et al. (1988) record global transgressive deposits and a sea level increase of ~50 m over ~0.5 myr in the lead up to the K/Pg boundary. Miller (2009) questioned the validity of these estimates while providing evidence of an abrupt transgression in the early Danian, alongside a composite eustatic trend line indicating a ~10 m sea level rise throughout the Danian on average. Early Danian sea level elevation has been corroborated by a range of foraminiferal studies (e.g., Brinkhuis and Zachariasse, 1988; Keller et al., 1993) and greater paleodepth resolution has been attained from work on transgressive system tracts in Europe and eastern North America (Esmeray-Senlet et al., 2015) as well as Africa (Farouk and Jain, 2016), signalling a highstand in the earliest Danian following a sea level rise of ≥ 25 m beginning below the K/Pg boundary. In the Oyster Bay Formation, this interpretation is generally in line with the succession of the Lynnwood beds from a lithostratigraphic standpoint supported by the composition of both the marine and terrestrial palynological assemblages.

In addition to lithological evidence, beds dominated by the *Glaphyrocysta* group with a marked decline in *Spiniferites* spp. abundance throughout Zone D2 appear to signal the onset of a major regressive phase (Crouch and Brinkhuis, 2005). These conditions give way to a more offshore assemblage within Zone D3, consisting of the highest relative abundances of *Areoligera volata*, *Cannosphaeropsis franciscana*, *Cordosphaeridium* spp., *Diphyes* spp. and *Hystrichosphaeridium tubiferum*. Species of *Areoligera* and *Hystrichosphaeridium* have had reported co-occurrence with increased relative abundance above the K/Pg boundary (Bowman et al., 2012; Vellekoop et al., 2017; Scasso et al., 2020). Many workers have tied *Areoligera* spp. abundance with more distal neritic settings (e.g., Iakovleva et al., 2001; Sluijs and Brinkhuis, 2009), as with *Cordosphaeridium* spp. (e.g., Downie et al., 1971; Powell et al., 1996), *Diphyes* (Van Mourik et al., 2001) and *H. tubiferum* (e.g., Brinkhuis, 1994; Açıkalın et al., 2015). *Cannosphaeropsis* is morphologically analogous to the open water to oceanic genus *Nematosphaeropsis*, therefore a similar habitat preference has been inferred (e.g., Brinkhuis and Biffi, 1993; Brinkhuis, 1994). The probable schizosporous algal cyst *Paralecaniella indentata* finds its highest abundance at the top of Zone D3 where specimen concentrations reach 628 cysts

g^{-1} in Sample 60 after having registered below 140 cysts g^{-1} throughout the succession. Concentrations of *P. indentata* only begin to exceed 100 cysts g^{-1} again in the middle of subzone D4b and in subzone D5b in the Oyster River section. *Paralecaniella* has been related to nearshore paleoenvironments with a suggested tolerance for brackish, inner neritic conditions (e.g., Elsik, 1977; Brinkhuis and Schiøler, 1996). Therefore, *P. indentata* may be among the earliest opportunistic responders to freshwater input at the D3–D4 zonal interface.

Similar phytoplankton turnovers are recognized across the K/Pg boundary in North Africa. At the Tunisian sites, including the basal Danian GSSP near El Kef, the *Glaphyrocysta* and *Spiniferites* groups are supplanted by increases in species of *Areoligera* and *Senegalinium* following a transgression (e.g., Brinkhuis and Leereveld, 1988; Vellekoop et al., 2015); the difference being a lowstand interpreted directly at the boundary near El Kef, but above it in the Elles section. Likewise, comparison can be made with the turnover documented at Ouled Haddou, Morocco (Slimani et al., 2010; Slimani and Toufiq, 2013), in that a shift toward the transgressive regime among these taxa marks the K/Pg boundary with the exception of increasing abundance of *Spiniferites* spp. across the interval. *Areoligera* in association with high-energy, transgressive conditions as opposed to a more offshore or lower energy setting for the *Spiniferites* group, is an interpretation favoured by a number of authors (e.g., Schiøler et al., 1997; Houben et al., 2019) and is consistent with the trend in the Lynnwood section. It is also noteworthy that the lower Oyster Bay Formation beds appear to have been deposited under sedimentation rates potentially in excess of an order of magnitude beyond the figures inferred in these and other well-studied intervals (e.g., Açıkalın et al., 2015; Vellekoop et al., 2016) implying that the Lynnwood section encompasses a sedimentary record of no more than the last ~100–200 kyr of the Maastrichtian based on the correlation of bioevents.

Dinoflagellate cyst diversity and taxa richness have been shown to correlate with regressive and transgressive sequences (Habib and Miller, 1989). The highest overall homogeneity along with the lowest diversity and taxa richness in Zone D2 pairs well with the interval of latest Maastrichtian regression. The values of these indices reaching their zenith at 3.6 m in the Appian Way section likely correspond to warmer, more stratified conditions with potential for upward mixing of deeper waters during peak sea level in the early Danian. The most homogenous assemblages, as well as among the lowest taxa richness and diversity occur at various points throughout the succession, such as at 40.8 m in Zone D3 of the Lynnwood section (Sample 51),

23.4 m in subzone D4b of the Appian Way section (Sample 79) and 1.5 m in subzone D5b of the Oyster River section (Sample 89). These peaks of *Areoligera* spp. dominance may represent niche capitalization of this resilient group within stressed, high-energy transitional settings near parasequence boundaries. The *Areoligera volata* complex was a major staple of the Late Cretaceous–early Paleocene phytoplankton community in the North Pacific also dominating assemblages within the upper Campanian Northumberland Formation on Hornby Island (McLachlan et al., 2018, 2019). Its higher relative abundances in the coarser-grained rocks of the Appian Way exposures suggests an association of heightened abundance under more turbulent neritic conditions.

The transition from a probable transgressive phase in Zone D3 to the base of Zone D4 marks the changeover from more coastal to estuarine, low salinity tolerant assemblages. Among the factors reflecting this shift are a series of distinct peridinioid increases occurring throughout the Danian represented by abundant to dominant *Senegalinium* spp. in the Appian Way mid-section and *Gingiodinium* cf. sp. A of Steeman et al. (2020) near the top of the section (Fig. 2.2). *Senegalinium* spp. occur sparsely before disappearing in the basal Lynnwood section only to return gradually in the uppermost Lynnwood beds after which they emerge forcefully above the presumed highstand at the top of Zone D3. *Senegalinium* has been considered indicative of high nutrient input due to upwelling (Nøhr-Hansen and Dam, 1997), terrestrial outflow (e.g., Sluijs et al., 2008; Vellekoop et al., 2017) and low water salinities (e.g., Sluijs et al., 2003; Sluijs and Brinkhuis, 2009; Woelders et al., 2017). Similarly, *Gingiodinium* has been linked to nutrient-rich waters (Steeman et al., 2020) and restricted marine conditions with salinity-related stresses (Guler et al., 2014, 2019). A major change among the cribroperidinioids is also marked above 3.6 m by the *Cordosphaeridium* group being overtaken by the *Exochosphaeridium* group (Fig. 2.2). This change is owing almost exclusively to *E. phragmites* dominance that persists until an *Operculodinium* spp. acme at the base of subzone D5b after more consistent appearances in the upper beds of subzone D4a (Fig. 2.2; Appendix 1.B, Table 1). *Exochosphaeridium phragmites* is another taxon which appears to characterize nearshore, low salinity paleoenvironments (e.g., Huan Li and Habib, 1996; Peyrot et al., 2012), along with *Operculodinium* spp., based on extant species which do well in neritic to estuarine water masses (e.g., Wall et al., 1977; Brinkhuis, 1994; Powell et al., 1996). *Xenikoon australis*, which is particularly prevalent in subzone D4b, has been related to brackish settings in association with *Paralecaniella indentata* (Heilmann-

Clausen, 1985) as is also the case in the Oyster Bay Formation. Lastly, there appears to be evidence of a minor transgressive pulse at the top of subzone D4b in the return of *Hystriosphæridium tubiferum* >5.0% in conjunction with the advent of *Gingiodinium* dominance (Fig. 2.2), suggesting that the latter may have increased to exploit heightened nutrient levels in more well-mixed waters toward the end of the Danian.

The reproductive components of terrestrial vegetation, pollen and spores are frequently deposited in marine sediments by way of water current transport (e.g., Heusser, 1988; Luo et al., 2016). Apart from biostratigraphy, their application can lend to the reconstruction of paleoshoreline proximity to the site of deposition through the establishment of a spore-to-pollen ratio beyond that of marine-to-terrestrial palynological constituents (e.g., Mudie and Harland, 1996; McCarthy and Mudie, 1998; Crouch et al., 2010) given that certain grains are lighter and more susceptible to long-range dispersal than others (e.g., Batten, 1996; Schwendemann et al., 2007; Grega et al., 2013). In the Oyster Bay Formation, a ~1:2 spore-to-saccate pollen ratio stands in harmony with the transgressive phase offshore marine palynological assemblages in Zone D3 before returning to a spore-dominated nearshore setting in Zone D4 and up-section. Modern C₃ land plants account for the vast majority of vegetation biomass and exhibit $\delta^{13}\text{C}_{\text{org}}$ values averaging -27‰ VPDB (e.g., O'Leary, 1988; Cerling et al., 2004), whereas values derived from marine phytoplankton in temperate to tropical shelf and open estuarine waters range from -18 to -24‰ VPDB (e.g., Fry and Sherr, 1984; Bird et al., 1995). The strong negative $\delta^{13}\text{C}_{\text{org}}$ values (avg. -26.36‰ VPDB) from coarse-grained clastic beds in the Oyster Bay Formation are a compelling signal of organic particulate enrichment corresponding to high-volume outflow of botanical material and terrestrial detritus (Appendix 2.D, SFig. 1). These are values within the range recorded for fluvial deposits in the Americas (e.g., Showers and Angle, 1986; Otero et al., 2000; Goñi et al., 2003), the North Sea (e.g., Salomons and Mook, 1981; Worden et al., 2019) and Africa (e.g., Gearing et al., 1977; Mariotti et al., 1991).

Schweitzer et al. (2009) conducted sedimentological analyses of several concretionary matrices from the Appian Way coastal exposures of the Oyster Bay Formation which bore decapod and molluscan macrofossils. The predominantly well-sorted, equigrained, muddy, silty matrix of these samples was interpreted as corresponding to that of a shallow, high-energy setting (Schweitzer et al., 2009). These findings are consistent with Zone D4 phytoplankton paleoecology lending to an interpretation of fluvial influence and deltaic conditions suitable for

ample terrigenous influx following a transgressive phase in Zone D3. This explanation would also account for the high volume of intermixed plant and marine macrofossil material previously studied (e.g., Mindell et al., 2014; Buczkowski et al., 2016; Haggart et al., in prep.). Furthermore, the high degree of microfossil pyritization in Zone D3 may reflect a setting of rapid organic matter burial within high-nutrient waters coupled with a high sedimentation rate conducive to suboxic conditions under which bacterial sulphate reduction lead to diagenetic pyrite formation (e.g., Berner, 1984; Schoonen, 2004). Within Zone D5 (Figs. 2.2 and 2.4), the approximated position of the Danian–Selandian boundary is marked below the advent of the thickest sandstone in the formation which forms the cliff face above the Appian Way intertidal outcrop. This feature draws comparison with a shift from carbonate to siliciclastic sediment deposition in the North Sea Basin (Clemmensen and Thomsen, 2005) linked to a major eustatic regression at this time (e.g., Schmitz et al., 2011; Hewaidy et al., 2019). Therefore, our data point to a nearshore setting with dinoflagellate cyst assemblages responding to paleoenvironmental changes across the K/Pg boundary in ways similar to those documented at other well-studied sections in the Northern Hemisphere.

2.7.5 Paleoproductivity

High dinoflagellate cyst concentrations and elevated taxa richness and diversity are considered to be factors indicative of high nutrient availability and primary productivity in both modern and ancient marine settings (e.g., Dale, 1996; Pospelova et al., 2008; de Vernal, 2009). Data pertaining to organic dinoflagellate cyst absolute abundance in proximity to the K/Pg boundary from elsewhere in the world are limited (Hultberg and Malmgren, 1986; Hansen et al., 1986; Vellekoop et al., 2019; Steeman et al., 2020), with most deep time studies considering the Cenomanian–Turonian boundary (Dodsworth, 2000, 2004; Dodsworth and Eldrett, 2019), as well as deposits of later Cretaceous age (Radmacher et al., 2015; McLachlan et al., 2018) and later early Paleogene age (e.g., Sluijs et al., 2009; Harding et al., 2011). Even though a direct comparison may not be advisable, cyst concentrations in modern sediments on the order of tens of thousands per gram is considered typical of high productivity environments (e.g., Pospelova et al., 2010). Levels $>10\text{k cyst g}^{-1}$ are reached consistently in the finest-grained beds of the Appian Way section, due in large part to increases in cysts of the *Areoligera volata* complex,

Senegalinium spp. and *Ginginodinium* cf. sp. A of Steeman et al. (2020) apart from isolated extremes such as the *Palynodinium grallator* acme in Sample 21 (Figs. 2.2, and 2.3).

Atmospheric circulation modelling has suggested that the western coast of North America was a region characterized by upwelling of nutrient-rich waters during Maastrichtian time (Hay, 2009). Episodes of heightened cyst concentrations throughout the Oyster Bay Formation punctuate a general trend of increasing taxa richness and diversity up-section, which may reflect a general early Danian marine food web recovery in conjunction with conditions of elevated nutrient input from localized sources.

Elevated peridinioid abundance has long been positively correlated with well-mixed coastal waters (e.g., Wall et al., 1977; Pross and Brinkhuis, 2005). Beyond figures of assemblage diversity and absolute abundance, the ratio between predominantly heterotrophic peridinioid or protoperidinioid cysts and those of autotrophic gonyaulacoid taxa has been applied by many researchers (e.g., Dale and Fjellsa, 1994; Guasti et al., 2006; Prauss, 2009) since its introduction as a paleo-upwelling signal (e.g., Harland, 1973; Powell et al., 1992b). The basis of this ‘P/G ratio’ as a paleo-upwelling signal is anchored in the premise that greater heterotroph numbers occur as a result of increased abundances of prey such as diatoms and other primary producer organisms. Sluijs et al. (2005) stress that the ratio cannot distinguish between upwelling and runoff-related primary productivity. Zonneveld et al. (2007, 2008) also emphasized caution in applying the metric as the true number of peridinioid cysts could be affected by aerobic degradation. However, most studies in the eastern North Pacific (e.g., Pospelova et al., 2008) have shown that this is not the case in highly productive regions with high sedimentation rates.

The exposure of dinoflagellate cysts to ultraviolet light has been used as an indicator of primary production capability through the illumination of chlorophyll (e.g., Wood, 1955; Pospelova and Head, 2002). McLachlan et al. (2018) demonstrated that members of deflandreoid genera of lighter pigmentation, such as *Spinidinium* and *Senegalinium*, respond to epifluorescence microscopy with brilliant illumination. This natural autofluorescence has also been confirmed within these genera in the present study as well as for specimens of *Ginginodinium*, albeit to a lesser extent in keeping with their gradation toward brown pigmentation. These findings support a possible mixotrophic feeding strategy for these taxa, therefore it may provide a more refined measure to ascertain values as they pertain exclusively to heterotrophic species. In the Oyster Bay Formation, solely heterotrophic peridinioids peak at

4.4% in Sample 77 from the mid- Appian Way section; an interval marked by some of the highest abundances of true heterotrophic taxa such as *Andalusiella gabonensis*, *Deflandrea galeata*, *Lejeunecysta* spp., *Octodinium askiniae*, *Palaeocystodinium golzowense* and *Phelodinium* spp. *Andalusiella gabonensis* and *O. askiniae* make their first appearance near the very top of the Lynnwood section, just above the FCO of *D. galeata* in approach to the early Danian highstand (Fig. 2.4). Although these taxa likely benefited from more open water upwelling conditions, there has been much discussion of a potential close association between heterotrophic deflandreoids and marginal marine to deltaic nearshore paleoenvironments (e.g., Brinkhuis et al., 1992, 1994; Firth, 1996). Thus, the scope of the peridinioid assemblages provides added weight toward the interpretation of a high primary productivity inner neritic setting for the Oyster Bay Formation.

2.8 Conclusions

This study is the first to demonstrate the presence of a conformable K/Pg boundary succession in the northeast Pacific. Global temporal indicator taxa within exquisitely preserved palynological assemblages allow placement of the Oyster Bay Formation as latest Maastrichtian–earliest Selandian in age spanning a ~4.5 to 5 myr record of marine phytoplankton community evolution within a ~93.5 m-thick package of fine-grained to coarse clastic sedimentary rock. The north-eastern Pacific occupied a unique position of paleobiogeographical significance during the K/Pg interval as reflected in a convergence of dinoflagellate cyst species of tropical, temperate and boreal provenance. This intermixing of latitudinally constrained dinoflagellate cyst taxa and the endemic signature of these assemblages carries implications for tracking the progression of Late Cretaceous–early Paleogene ocean circulation patterns within a regional biostratigraphic framework bolstered by the extinction and emergence of key cosmopolitan index species tied to the K/Pg event. Fluctuations in abundance between competing dinoflagellate cyst ecogroups across four families (Areoligeraceae, Goniodomaceae, Gonyaulacaceae and Peridiniaceae) provide compelling evidence of sea level change from an end-Cretaceous regression to a transgressive phase in the early Paleocene, likely corresponding to widescale climatic shifts. The marine palynological assemblages also lend insight into phytoplankton paleoecological responses to changes in localized marine conditions. An array of marine palynomorphs indicates

episodes of elevated nutrient availability, primary productivity and likely stratification in the upper water column through elevated specimen concentrations and relative abundances of dinoflagellate cysts such as those of heterotrophic peridinioids. An overarching trend in increasing dinoflagellate cyst taxa richness, diversity and assemblage heterogeneity throughout the succession is observed in conjunction with a major transition from coastal to more estuarine conditions above the K/Pg boundary. Multiple marine and terrestrial palynological signals reinforce a predominately neritic paleoenvironment punctuated by periods of brackish water incursion occurring with prevalence and prolonged duration in the Danian. Alternating low-energy and high-energy systems are apparent in the sequence stratigraphy of the formation with inference of fluvial influence supported by lithology and $\delta^{13}\text{C}_{\text{org}}$ geochemistry. The prevailing interpretation is one of a depositional setting situated near the margin of the Nanaimo Basin of varying proximity to a river plume with oscillations in volume outflow and nutrient delivery; these waters were less productive during the regressive phase at the close of the Maastrichtian becoming increasingly well-mixed and prolific with likely greater upwelling coinciding with the early Danian transgression and more terrestrial outflow toward the Selandian.

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Chapter 3

Vesiculation in the dinoflagellate cyst

Cannosphaeropsis franciscana Damassa, 1979

across the K/Pg boundary (Vancouver Island, Canada) with implications for spiniferate gonyaulacacean taxonomy and ecophenotypy¹

3.1 Contributions of authors

All of the content presented herein—from conceptualization to the figures, data, analyses, results, discussions and conclusions—was produced by the lead author with the exception of the scanning electron microscopy (SEM) images which were rendered and cleaned up in post-production by Dr. Elaine Humphrey who also provided funding for this research. In addition to lending assistance with the methodology and review of the manuscript, Dr. Vera Pospelova assumed an advisory role from which the study improved following her influence on the data presentation and discussions relating to the ecology of modern taxa.

3.2 Abstract

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Wall structure and process type have long been essential taxonomic characters used in generic and specific determinations among spiniferate gonyaulacacean dinoflagellate cysts. We observe solid to fully vesiculate wall structure as well as a range of surface texture and process development all within a suite of over 400 specimens of the species *Cannosphaeropsis franciscana* recovered from the sedimentary rocks of the upper Maastrichtian–lower Selandian Oyster Bay Formation, Vancouver Island (British Columbia, Canada). The genus *Cannosphaeropsis* is herein provided with an emended diagnosis and description to accommodate this variability as is the species *Cannosphaeropsis franciscana* which represents a plexus of conspecific morphology unparalleled within the fossil Gonyaulacaceae. In addition, we propose three subspecies of *Cannosphaeropsis franciscana*: *Cannosphaeropsis franciscana* subsp. *franciscana* (autonym), *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov., and *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov. Most vesiculate forms of the species are stratigraphically constrained to within localized Dinoflagellate Cyst Zone D3 situated immediately above the K/Pg boundary. Vesicles are suggested as an adaptation prolonging cyst buoyancy in the water column. Within *C. franciscana*, prominent vesiculation occurs during an interval characterized by unstable, stratified marine conditions associated with the post-Cretaceous transgressive phase. Assemblage data throughout the formation also indicate that members of the vesiculate genus *Hafniasphaera* increase abundances in nutrient-rich and likely stratified coastal waters when *Spiniferites* species are also abundant. The paleoecology of *Cannosphaeropsis* and the value of these dinoflagellate cysts as paleoenvironmental indicators is considered as well as all currently accepted members of the genus and their chronostratigraphic and geographic distributions.

3.3 Introduction

Organic-walled dinoflagellate cysts, the resting stages of a major group of unicellular microalgae, have been shown to be of great utility for relative dating and paleoenvironmental reconstruction in Mesozoic and Cenozoic studies due to their frequent abundance as well as the wide distribution in marine environments and narrow chronostratigraphic constraints of many forms (e.g., Stover et al., 1996; Williams et al., 2004; Fensome et al., 2008). Dinoflagellate cysts have been of particular value as indices for tracing paleoenvironmental conditions in relation to

major and minor events in Earth history since the Middle Triassic when they unequivocally emerged in the fossil record (e.g., Fensome et al., 1996; Riding et al., 2010). Much research as of late has focused on the dinoflagellate cyst record across the K/Pg boundary during the interval of the end-Cretaceous mass extinction (e.g., Țabăără and Slimani, 2017; Vellekoop et al., 2017; Chakir et al., 2020). A K/Pg boundary section has recently been discovered in the north-eastern Pacific (Vancouver Island, British Columbia) for the first time, using dinoflagellate cysts as biostratigraphic tools (McLachlan and Pospelova, in press) which also reveal paleoecological signals consistent with those observed elsewhere in the Northern Hemisphere (e.g., Slimani et al., 2010; Slimani and Toufiq, 2013) including the Global Stratotype Section and Point for the base of the Danian Stage near El Kef, Tunisia (e.g., Brinkhuis and Leereveld, 1988; Vellekoop et al., 2015). Dinoflagellate cysts are both abundant and diverse at this site, presenting the opportunity to measure phytoplankton responsivity to both localized and widescale environmental change across the interval following the terminal Cretaceous event given the occurrence of numerous cosmopolitan taxa.

The genus *Cannosphaeropsis* consists of extinct spiniferate gonyaulacacean dinoflagellate cysts known from both northern and southern hemispheres with species occurrences ranging from the Early Cretaceous (e.g., Harding, 1990) to the Pliocene (e.g., Besems, 1993). A total of seven species are presently recognized which include: the type species, *Cannosphaeropsis utinensis* Wetzel, 1933, as well as *Cannosphaeropsis australis* Riding and Helby, 2001, *Cannosphaeropsis franciscana* Damassa, 1979, *Cannosphaeropsis hughesii* Harding, 1990, *Cannosphaeropsis passio* de Verteuil and Norris, 1996, *Cannosphaeropsis quattrocchia* Guerstein et al., 2001 and *Cannosphaeropsis williamsii* Sarjeant, 1986 (Fensome et al., 2019). The species *Cannosphaeropsis franciscana* Damassa, 1979 was found in the sedimentary rocks of the Oyster Bay Formation exposed on eastern Vancouver Island, British Columbia (Fig. 3.1) (McLachlan and Pospelova, 2021). Except for a single European record (Slimani et al., 2011), *C. franciscana* is a species largely restricted to the north-eastern Pacific, and otherwise known only from California (Drugg, 1967; Damassa, 1979) and British Columbia (McLachlan and Pospelova, 2021). The palynological assemblages recovered from the Oyster Bay Formation (McLachlan and Pospelova, 2021) have presented the opportunity for new phytoplankton-based paleoecological and paleoenvironmental insights as revealed through this enigmatic member of an understudied genus from a frontier region for marine palynology.

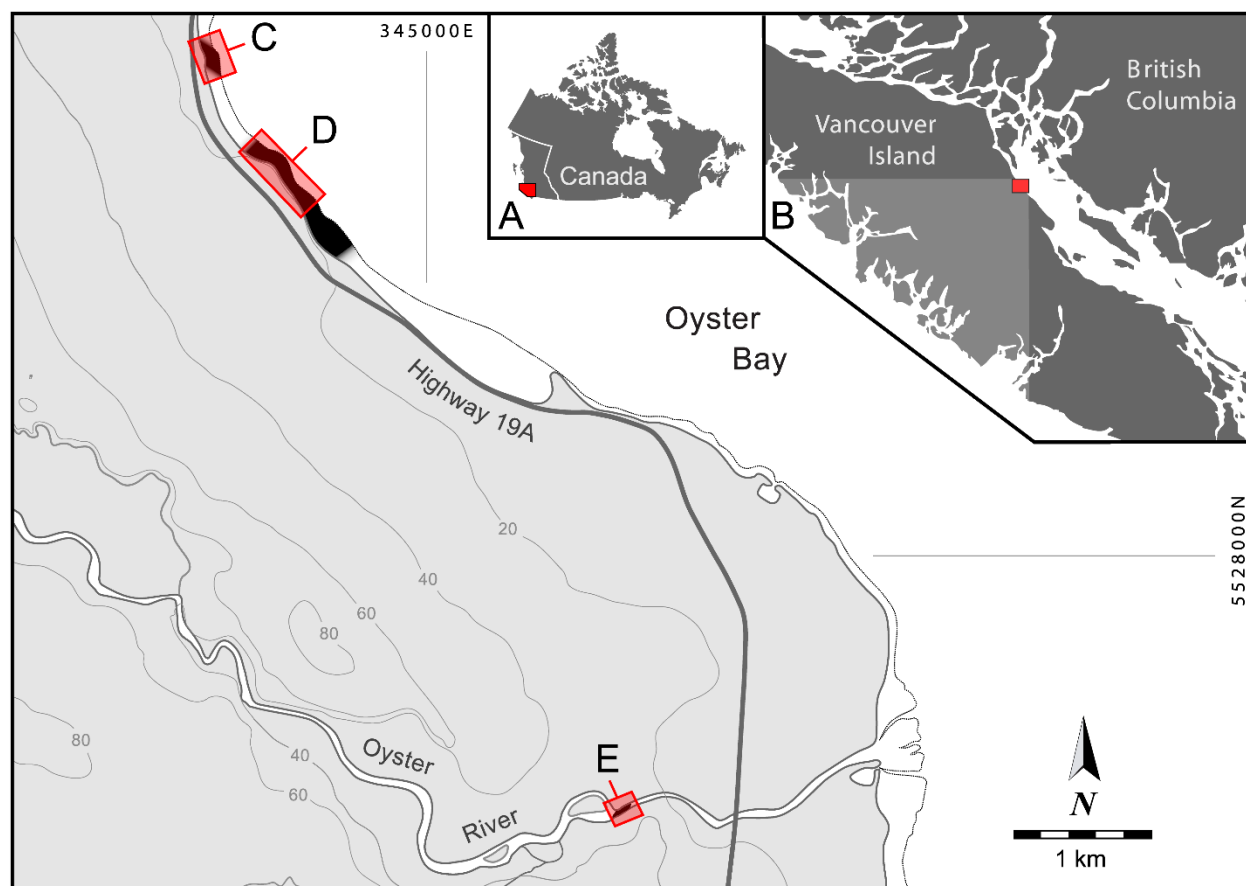


Figure 3.1. **A**, Location of Vancouver Island, British Columbia, Canada; **B**, Location of the study area and Oyster Bay Formation localities, east coast Vancouver Island; **C**, Lynnwood coastal section; **D**, Appian Way coastal section; **E**, Oyster River section. Blackened areas denote outcrop.

3.4 Geological setting

Marine sedimentary rocks of Late Cretaceous–early Paleogene age are sparsely distributed throughout the north-eastern Pacific realm with lower Paleocene–middle Eocene strata unconformably overlying those of the Upper Cretaceous Nanaimo Group across eastern Vancouver Island and the Gulf Islands, extending into lower mainland British Columbia and north-western Washington State (e.g., Mustard and Rouse, 1992, 1994; Mustoe et al., 2007; Mathewes et al., 2020). Recent study of the as yet informally named Oyster Bay Formation (Haggart et al., in prep.) situated south of Campbell River on eastern Vancouver Island (Fig. 3.1) has revealed this unit to encompass the K/Pg boundary interval based on age-diagnostic

dinoflagellate cysts and a detailed survey of the marine palynological assemblages therein (McLachlan and Pospelova, 2021). The Oyster Bay Formation unconformably overlies Nanaimo Group rocks of the Santonian–Campanian Haslam Formation (e.g., Haggart and Graham, 2018; Coutts et al., 2020) and lower–upper Campanian Cedar District Formation (e.g., Enkin et al., 2001; Ward et al., 2012). The Haslam Formation crops out along the banks of the Oyster River 1.5 km upstream and to the east of the uppermost Oyster Bay Formation beds at the terminus of Lorna Lane and the Cedar District Formation forms an expansive coastal outcrop at Shelter Point, long renowned for its marine invertebrate fossils (Richards, 1975; Ward, 1978) 1.9 km north of the basal Oyster Bay Formation exposures. McLachlan and Pospelova (2021) subdivided the Oyster Bay Formation into five dinoflagellate cyst zones and four subzones spanning the upper Maastrichtian–lower Selandian and the formation is represented as a ~93.5 m-thick succession with a lateral extent over at least 6.5 km based on a composite of three sections measured from the Lynnwood, Appian Way, and Oyster River exposures (Fig. 3.2). The sedimentary rocks of Zone D4 within the Appian Way section have been the most extensively investigated lower Paleogene strata in the region which have yielded a rich paleobotanical fossil record (e.g., Smith et al., 2004; Mindell et al., 2006, 2014; Atkinson et al., 2015) along with a diverse array of molluscs, decapods, corals and shark teeth (e.g., Haggart et al., 1997, in prep.; Schweitzer et al., 2009).

3.5 Materials and methods

A total of 90 sedimentary rock samples were processed for palynological analysis throughout the Oyster Bay Formation succession; 56 were obtained from the Lynnwood section, 31 from the Appian Way section and three from the Oyster River section (McLachlan and Pospelova, 2021). Stratigraphic section abbreviations used in conjunction with sample positioning herein are: AW = Appian Way; LN = Lynnwood; OR = Oyster River. Three samples were taken from float concretionary matrices collected at the Appian Way locality during the pilot phase of this study. Thirty-nine samples were extracted over 5.3 m above the base of the Lynnwood section where higher resolution sampling was conducted as part of the initial investigation to constrain the K/Pg boundary due to the presence of several predominantly Cretaceous palynological taxa range tops within this interval. The stratigraphic position of each sample is plotted in Fig. 3.2.

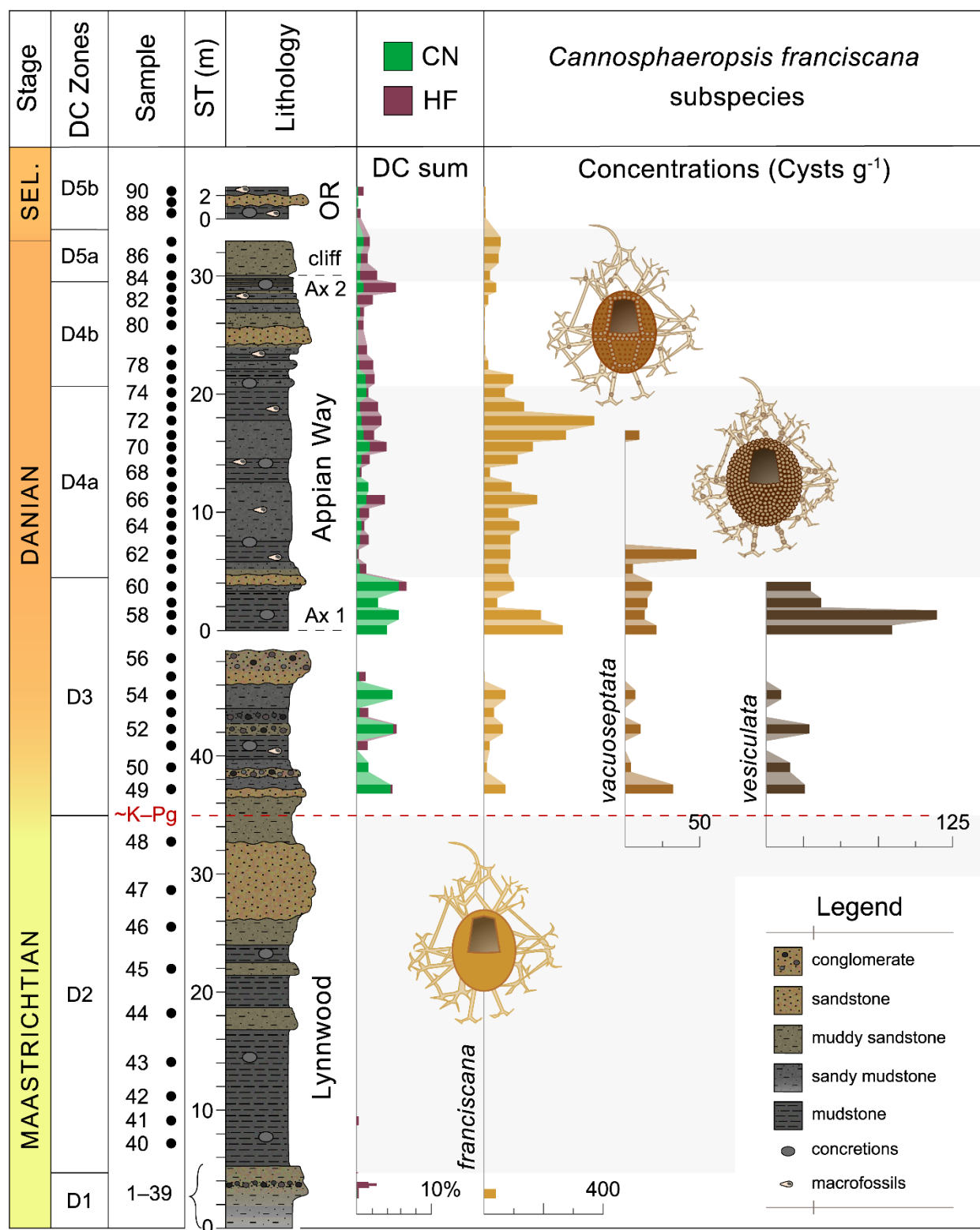


Figure 3.2. Schematic framework of the measured sections of the Oyster Bay Formation and dinoflagellate cyst zones of McLachlan and Pospelova (2021) with plotted relative abundances (stackable)

%), stratigraphic ranges and cyst concentrations (cysts g^{-1}) of the three *Cannosphaeropsis franciscana* subspecies; *Cannosphaeropsis franciscana* subsp. *franciscana* (autonym), *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov. and *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov. DC = dinoflagellate cyst(s). ST = stratigraphic level above base of section. CN = *Cannosphaeropsis franciscana*. HF = *Hafniasphaera* spp.

Samples were prepared using a standardized dinoflagellate cyst extraction procedure (e.g., Pospelova et al., 2010). For each of the samples, subsamples of $\sim 2 \text{ cm}^3$ of matrix were placed in 50 ml polypropylene test tubes with the dry weights of these samples averaging $\sim 5.4 \text{ g}$. Samples were treated repeatedly with 10 ml of 10% room-temperature hydrochloric acid (HCl) in order to dissolve any carbonates. A single *Lycopodium clavatum* tablet of batch #177745 (18584 ± 1853 spores per tablet, produced at the Department of Geology, University of Lund, Lund, Sweden) or batch #2013001 ($27,560 \pm 2643$ spores per tablet, produced at the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing, China) was added to each sample to enable calculations of dinoflagellate cyst concentrations (e.g., Benninghoff, 1962; Stockmarr, 1971; Mertens et al., 2009b, 2012c).

Following hydrochloric acid (HCl) treatment, the samples were placed in 20 ml of 48% room-temperature hydrofluoric acid (HF) where they were left to sit with daily stirring for an average of two weeks. Afterward, each sample underwent one round of HCl and two rinses of reverse osmosis water to remove any HF residue before final sieving through $120 \mu\text{m}$ and $15 \mu\text{m}$ Nitex nylon mesh to remove remaining particles. The samples underwent up to 1 min of ultrasonic agitation (Mertens et al., 2012c; Price et al., 2016) to dislodge any minute sediment particles from the dinoflagellate cysts and centrifuging took place at 3600 rpm. Following sieving, residue was mounted in glycerin jelly on microscope slides for bright-field microscopy. Unless otherwise stated, all microfossil samples are assigned catalogue numbers and are housed within the Paleoenvironmental/Marine Palynology Laboratory, School of Earth and Ocean Sciences, University of Victoria (UVic; Victoria, British Columbia, Canada) and Advanced Microscopy Facility (University of Victoria, Victoria, Canada).

Dinoflagellate cyst identification and counts were conducted at 600x magnification wherein a single specimen was recorded if more than half its structure was intact (operculum notwithstanding). Counts exceeding 400 dinoflagellate cysts were reached where possible (e.g.,

Slimani et al., 2010, 2016) over a maximum of four slides to obtain optimal relative abundance distributions in high-diversity assemblages beyond the statistically sufficient sample size of 300 cysts as determined for Quaternary sediment analyses (Mertens et al., 2009b). An average of 420 dinoflagellate cysts were counted across the 71 most productive samples which yielded concentrations of >50 cysts g^{-1} (McLachlan and Pospelova, 2021). Where present, specimens of *Cannosphaeropsis franciscana* were counted relative to at least 1% of the introduced *Lycopodium clavatum* spores from each tablet as to place a controlled threshold on their sample size. A series of measurements were taken from selected specimens of *C. franciscana* where possible in accordance with specimen integrity and orientation (Fig. 3.3).

Bright-field photomicrographs were taken under 600x or 1000x magnification with a Nikon DS-5M-L1 digital camera system mounted on a Nikon Eclipse 80i light microscope. For clarity of image presentation, extraneous particulate debris were removed from the field of view (Riding and Head, 2018) with a brush tool using Macromedia Fireworks 8 software if the particles were not in direct contact with the specimen ambitus. Epifluorescence was used as an indicator of the original chlorophyll presence (e.g., Wood, 1955; Lessard and Swift, 1986; Brenner and Biebow, 2001; Pospelova and Head, 2002) and photomicrographs of selected specimens were taken with epifluorescence mode after exposing them to ultraviolet light for a minimum of 2 min using a Nikon Intensilight C-HGFI precentred fiber illuminator. Specimens prepared for SEM underwent up to an additional 4 min of ultrasonic agitation following sieving prior to being transferred to aluminum SEM stubs with a micropipette. SEM stubs were then coated with either gold or a gold/palladium mix using either an Edwards S150B or Anatech Hummer VI sputter coater for a thickness of 10–50 nm. Surface ablation was performed on selected specimens using a Hitachi FB2100 focused ion beam to aid in autophragm internal structure analysis. Micrographs of selected specimens were taken using a Hitachi S-4800 SEM at the Advanced Microscopy Facility (University of Victoria, Victoria, Canada) and composite images were prepared for optimal presentation using Adobe Bridge CC 2017 and Adobe Photoshop CS6 software.

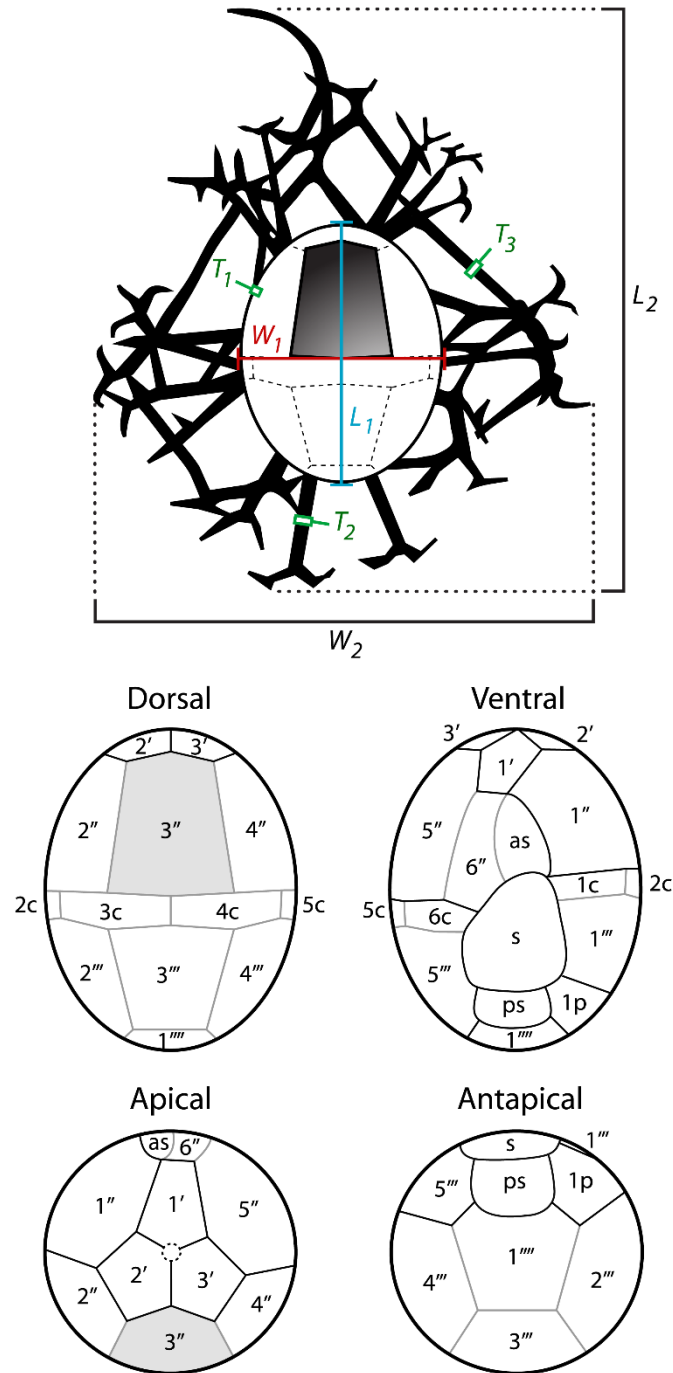


Figure 3.3. Measurement scheme and inferred gonyaulacoid tabulation applied to specimens of *Cannosphaeropsis franciscana* in the present study. L_1 = autophragm length. W_1 = autophragm width. L_2 = ectophragm length. W_2 = ectophragm width. Structure thickness (T) measurement series were taken as averages of three readings. Plate boundaries in gray are those not reflected by ectophragm trabecular network.

3.6 Results

3.6.1 Marine palynology

The marine palynological assemblages of the Oyster Bay Formation are highly diverse with the entire succession yielding over 100 dinoflagellate cyst species across six families from those samples which were productive (McLachlan and Pospelova, 2021). All cysts of *Cannosphaeropsis franciscana* are generally very well preserved throughout the section and were identified from forty-three of the 90 samples (Plates 3.1–3.12). The epifluorescence of these cysts (Plate 3.3, figs. 8–10) suggests an autotrophic (or phototrophic) affinity. Three subspecies have been recognized herein and their concentrations are plotted against the measured sections of the formation and the dinoflagellate cyst zones defined by McLachlan and Pospelova (2021) (Fig. 3.2). Specimen counts and concentrations data are presented in Appendix 2.A. The provenance of three float concretionary matrices (Appendix 2.A, samples 75, 77, and 85) has been inferred through lithological and palynological assemblage correlation, although their data have been excluded from the Fig. 3.2 plots due to imprecision of their stratigraphic positioning and probable in-situ sample equivalence.

Specimens of *C. franciscana* are generally rare throughout the succession, averaging 1.5% of the dinoflagellate cyst assemblages when present. In Zone D1, the species is present only in Sample 21 (LN 3.1 m) represented by *C. f.* subsp. *franciscana* at its lowest relative abundances (0.04%) due to an overwhelming dominance of *Palynodinium grallator* and at a concentration of 31 cysts g⁻¹. The species then becomes absent in Zone D2 only to re-emerge in Zone D3 where it reaches its highest relative abundances (avg. 3.3%) accounting for up to 5.8% of all dinoflagellate cysts in samples 54 (LN 45 m) and 60 (AW 3.6 m) with an overall average of ~123 cysts g⁻¹. Conversely, the species has its lowest concentration in Sample 55 (LN 46.5 m) at 0.4 cysts g⁻¹ due to a major *Areoligera volata* acme near the top of the Lynnwood section. Zone D3 also records the first occurrences (FOs) of the densely vesiculate subspecies *C. f.* subsp. *vacuoseptata* subsp. nov. and *C. f.* subsp. *vesiculata* subsp. nov. in Sample 49 (LN 37.4 m) immediately above the K/Pg boundary. On average throughout Zone D3, specimens of *C. f.* subsp. *vacuoseptata* subsp. nov. and *C. f.* subsp. *vesiculata* subsp. nov. comprise 10.4% and 20.3% of the assemblages, respectively. Only in Sample 50 (LN 39 m), just above their FOs, these variant forms become dominant within the species (*C. f.* subsp. *vacuoseptata* subsp. nov.:

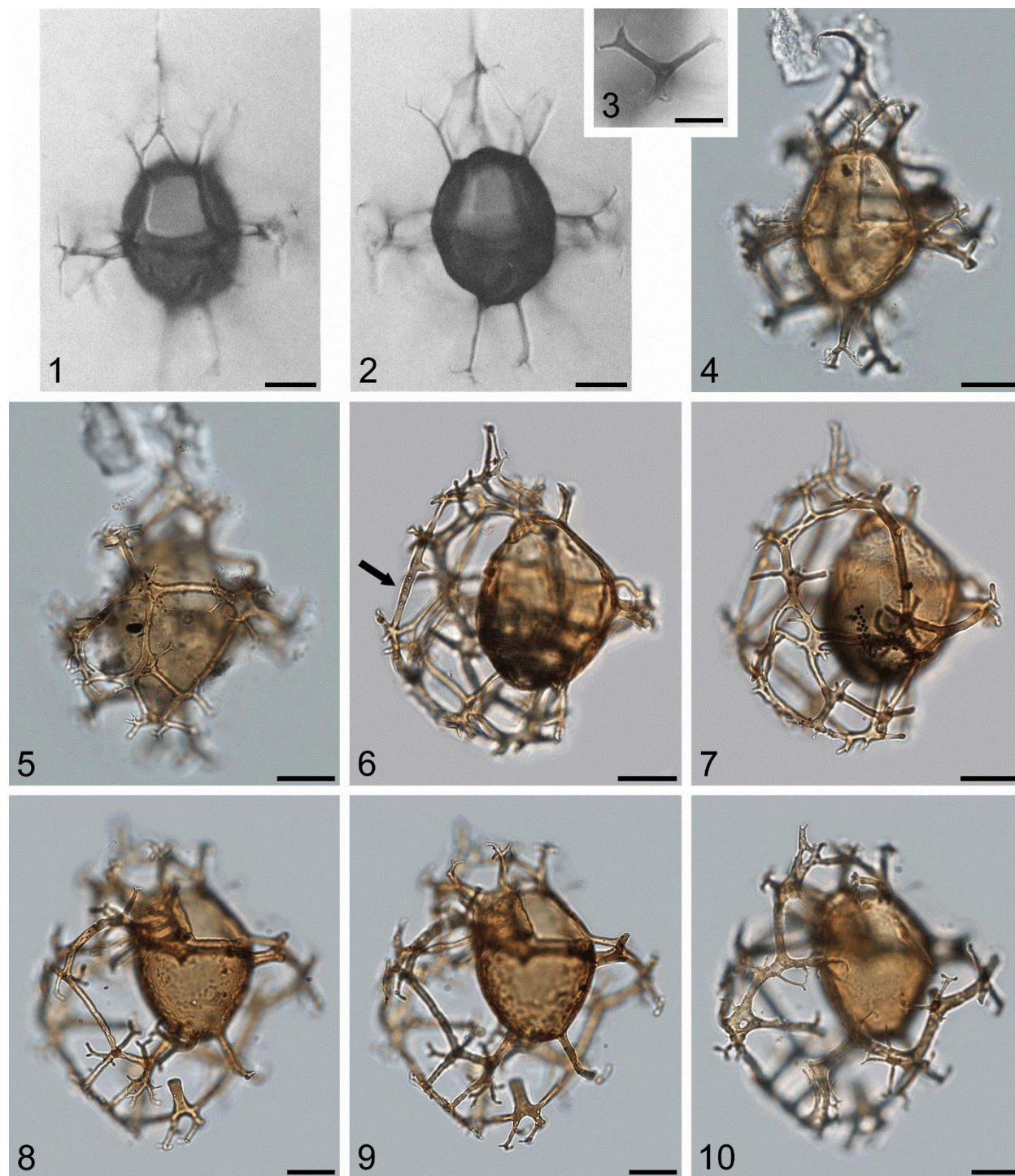


Plate 3.1. Bright-field photomicrographs of *Cannosphaeropsis franciscana* subsp. *franciscana* specimens. Oyster Bay Formation section abbreviations: AW = Appian Way; OR = Oyster River. 1–3, holotype of Damassa (1979, pl. 5, figs. 1, 2, 6) from the Danian of the Franciscan Complex, California; 1, dorsal view with archaeopyle in focus, scale bar = 20 μm (derived from x384 magnification given in publication); 2, dorsal view, mid-focus, scale bar = 20 μm (derived from x384 magnification given in

publication); 3, ramosus-type distal process termination with primary trifurcation and secondary bifurcations, scale bar = 10 μm (derived from x960 magnification given in publication). 4, 5, plesiotype, AW 21.8 m, Sample 78 (UVic 17-692, slide D, EF: L29/2), scale bars = 20 μm ; 4, left dorsolateral view with curved apical horn; 5, right ventrolateral view of trabecular ring. 6, 7, plesiotype, AW 13.5 m, Sample 68 (UVic 18-232, slide A, EF: T36/1), scale bars = 20 μm ; 6, lateral view, autophragm mid-focus with trabecular vesicles in focus (arrow); 7, left ventrolateral view, trabecular junctions in focus. 8–10, plesiotype, OR 2.3 m, Sample 90 (UVic 17-694, slide B, EF: G37/0), scale bars = 20 μm ; 8, left dorsolateral view, autophragm surface texture at one-fifth focus; 9, lateral view, autophragm wall thickness at mid-focus; 10, right ventrolateral view, robust trabeculae and rare reflected intergonal trabecular projection in focus.

14.3%; *C. f. subsp. vesiculata* subsp. nov.: 57.1%). Zone D4 sees a drop in the relative abundance of *C. franciscana* to nearly one fifth of Zone D3 levels (avg. 0.7%) with an overall average of ~ 98 cysts g^{-1} . Subzone D4a has the highest concentrations of specimens averaging ~ 133 cysts g^{-1} before an over fivefold decrease that occurs in subzone D4b to an average of ~ 26 cysts g^{-1} . *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov. has its last occurrence (LO) at the top of Zone D3 in Sample 60 (AW 3.6 m) while *C. f. subsp. vacuoseptata* subsp. nov. is present in samples 61 and 62 at the base of subzone D4a with a single spot occurrence marking its range top in Sample 71 (AW 17 m). Zone D5 exhibits the lowest relative abundances of *C. franciscana* in an interval with consistent occurrence (avg. 0.5%). Subzone D5a at the top of the Appian Way section yields concentrations averaging ~ 42 cysts g^{-1} . This figure drops ninefold in subzone D5b to an overall average of ~ 5 cysts g^{-1} in the Oyster River section.

3.6.2 Systematic paleontology

The approach to classification and nomenclature follows that of Williams et al. (2017) and Fensome et al. (2019). The conventional Kofoed Tabulation System (Kofoed, 1907a, 1907b, 1909, 1911) is employed in plate identification. Other descriptive morphological terminology draws from that of Below (1987), Fensome and Williams (2005) and Londeix et al. (2018). Measurements obtained from specimens analyzed through both transmitted light microscopy and SEM are listed in Appendix 2.B. England Finder (EF) coordinates are provided for type and

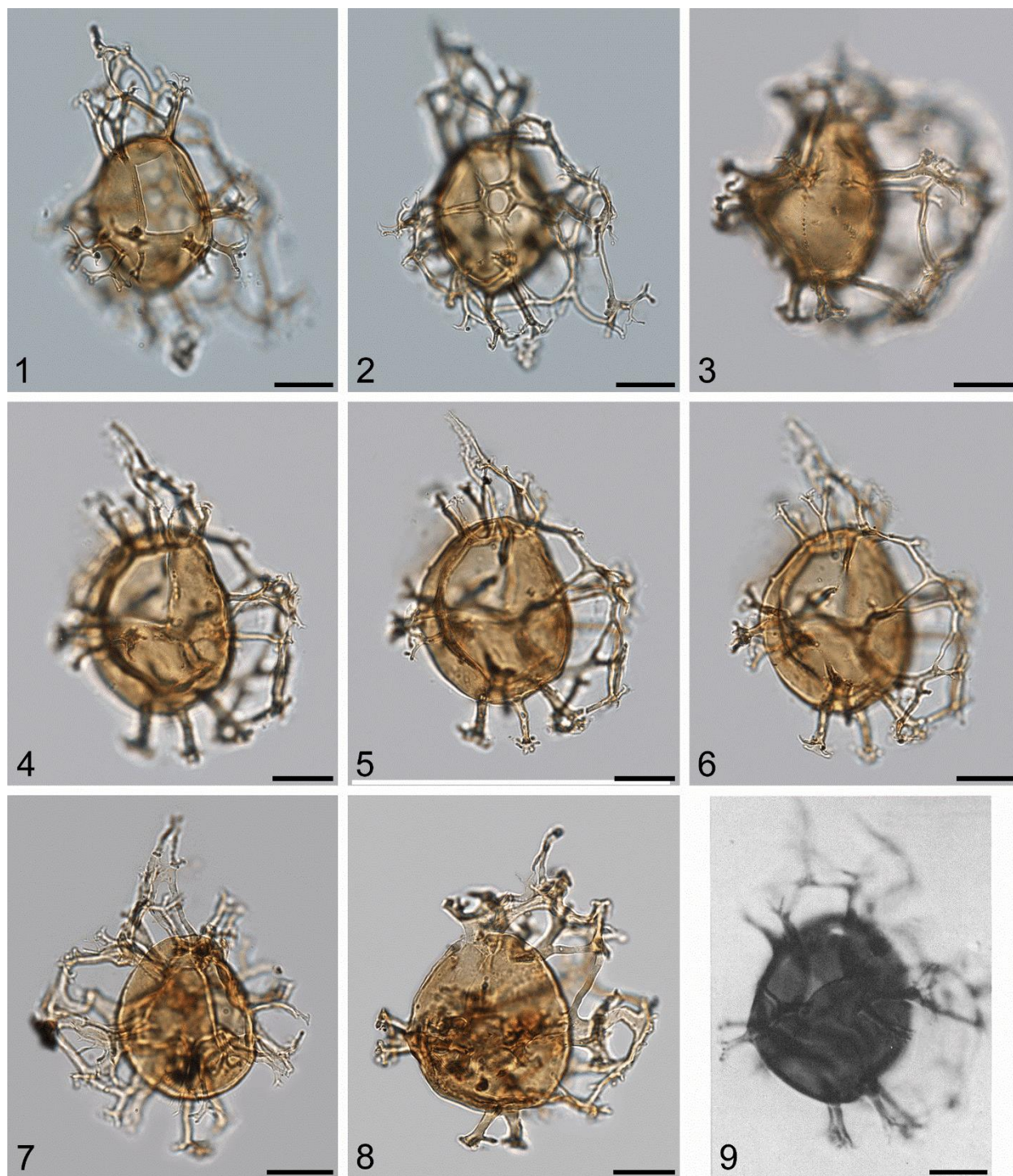


Plate 3.2. Bright-field photomicrographs of *Cannosphaeropsis franciscana* subsp. *franciscana* specimens. Oyster Bay Formation section abbreviations: AW = Appian Way; LN = Lynnwood. 1, 2, plesiotype, LN 3.1 m, Sample 21 (UVic 18-184, slide B, EF: R34/0), scale bars = 20 μ m; 1, left dorsolateral view, archaeopyle with sutural beading along 2''–3'' plate boundary in focus; 2, right ventrolateral view of constricted trabecular ring. 3, plesiotype, LN 45 m, Sample 54 (UVic 18-182, slide

A, EF: E32/2), right lateral view with sutural beading along 3'''–4''' plate boundary in focus with intratabular vesiculate protuberances on plate 5''', scale bar = 20 µm. 4–6, plesiotype, LN 3.1m, Sample 21 (UVic 18-184, slide F, EF: R25/0), scale bar = 20 µm; 4, right dorsolateral view with sutural beading along 3''–4'' plate boundary in focus; 5, right dorsolateral view, autophragm at one-quarter focus, note isolated vesicles within the 3'''–1'''–4''' triple junction process; 6, left ventrolateral view with slender trabecular network in focus. 7, plesiotype, AW 1.3 m, Sample 58 (UVic 18-181, slide C, EF: W43/3), left dorsolateral view, morphotype with septentrionalis-type distal process terminations, scale bar = 20 µm. 8, plesiotype, AW 1.3 m, Sample 58 (UVic 18-181, slide C, EF: N34/0), right dorsolateral view, morphotype with blunt pseudofurcatus-type distal process terminations and operculum attached, scale bar = 20 µm. 9, specimen originally figured by Drugg (1967, pl. 4, fig. 16) from the Danian of the Moreno Formation, California, as *Cannosphaeropsis filifera* and re-illustrated by Damassa as a paratype (1979, pl. 5, figs. 8, 9); note the apparent pseudofurcatus-type distal process terminations, scale bar = 20 µm (derived from dimensions provided by Drugg (1967, p. 26).

reference specimens recovered from the Oyster Bay Formation observed in this study. The coordinates are taken with the slide label to the right.

Division: DINOFLAGELLATA (Bütschli, 1885) Fensome et al., 1993

Subdivision: DINOKARYOTA Fensome et al., 1993

Class: DINOPHYCEAE Pascher, 1914

Subclass: PERIDINIPHYCIDA Fensome et al., 1993

Order: GONYAULACALES Taylor, 1980

Suborder: GONYAULACINEAE (autonym)

Family: GONYAULACACEAE Lindemann, 1928

Subfamily: GONYAULACOIDEAE (autonym)

Genus: **CANNOSPHAEROPSIS** Wetzel, 1933 emend. nov.

Type species: *Cannosphaeropsis utinensis* Wetzel, 1933, pl. 3, figs. 9–17, text-fig. 12; lectotype by designation of Sarjeant (1985, pl. 5, figs. 1, 2).

Emended diagnosis: Gonyaulacacean (gonyaulacoid) spiniferate cysts that are proximochorate to chorate with subspherical to elongate subhexagonal central body ambitus. Acavate with trabecular ectophragm. Processes, if present, typically gonal, sutural, arising from at least the ventrolateral surfaces linked below distal terminations by singular trabeculae that

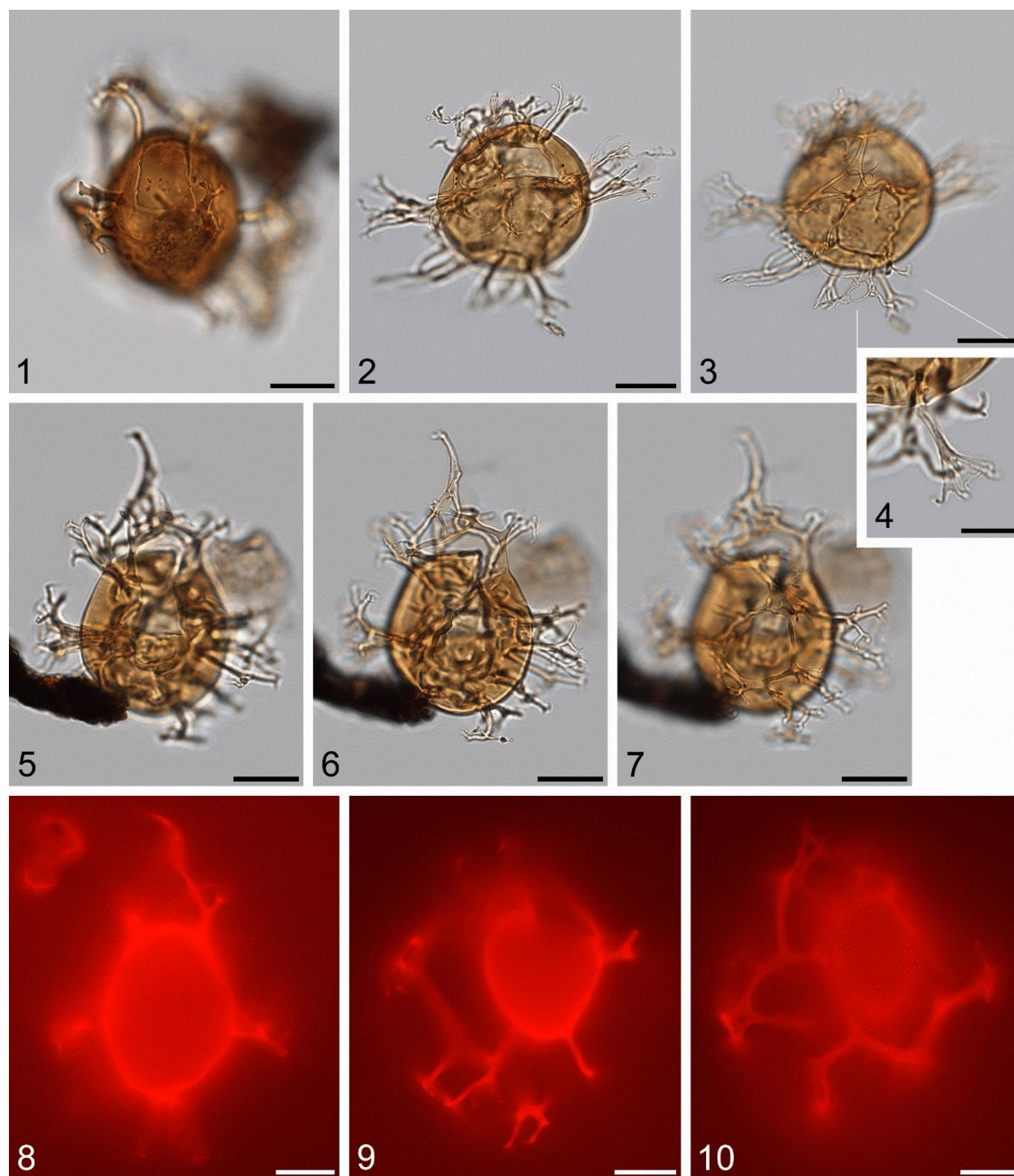


Plate 3.3. Bright-field photomicrographs and epifluorescence imaging of *Cannosphaeropsis franciscana* subsp. *franciscana* specimens. Oyster Bay Formation section abbreviations: AW = Appian Way; OR = Oyster River. 1, plesiotype, AW 31.5 m, Sample 86 (UVic 19-83, slide A, EF: L41/3), dorsal view with operculum attached, scale bar = 20 μm . 2–4, plesiotype, AW 31.5 m, Sample 86 (UVic 19-83, slide A, EF: O36/4); 2, dorsal view with archaeopyle in focus and gracile, multifurcate processes, scale bar = 20

µm; 3, ventral view with trabecular ring in focus, scale bar = 20 µm; 4, enlarged view of septentrionalis-type fenestrate distal termination of the 3'''–1'''–4''' triple junction process, scale bar = 10 µm. 5–7, plesiotype, AW 31.5 m, Sample 86 (UVic 19-83, slide B, EF: V39/1), scale bar = 20 µm; 5, dorsal view with archaeopyle in focus; 6, slender apical horn and ramosus-type distal process terminations in focus; 7, ventral view with trabecular ring in focus. 8, plesiotype, AW 21.8 m, Sample 78 (UVic 17-692, slide D, EF: L29/2), specimen epifluorescence at mid-focus, scale bar = 20 µm. 9, 10, plesiotype, OR 2.3 m, Sample 90 (UVic 17-694, slide B, EF: G37/0), scale bars = 20 µm; 9, specimen epifluorescence in left dorsolateral view, autophragm one-quarter focus; 10, specimen epifluorescence in right ventrolateral view, trabecular network in focus.

reflect sutural boundaries; stems absent in at least the ventral sulcal region; vesiculation may be present. Archaeopyle isosceles trapezoidal to subpentagonal precingular (isodeltaform camerate), with formula P_3'' , usually operculum free.

Emended description: Autophragm may be smooth to sparsely microgranulate, granulate, foveolate, to densely vesiculate. Processes typically gonial and sutural with distal process termination (DPT) variability ranging from elongate tri- and bifurcate to lamellar, fenestrate, petaloid. Rare intergonial process may occur as well as rare instances of sutural ridges along plate boundaries connecting gonial processes stems.

Remarks: In encompassing forms so elaborate in structure and ornamentation, *Cannosphaeropsis* was initially regarded to be a radiolarian genus (Wetzel, 1933, 1940; Deflandre, 1935, 1937; De Wit, 1943) even though its general composition was recognized to be organic from the outset (Wetzel, 1933; Deflandre, 1937). It would be over a decade until Deflandre (1947) would correctly place the type species *Cannosphaeropsis utinensis* Wetzel, 1933 as a chorate dinoflagellate cyst while resolution of the distinction between members of the Dinoflagellata and Radiolaria would remain in its infancy into the 1960s (e.g., Loeblich Jr. and Loeblich III, 1969; Wetzel, 1961). Wetzel's (1933, p. 6) description of the genus was essentially comparative in stating resemblance to "the radiolarian *Cannosphaera*; however, distinct from it from outside (as from *Coelacantha*) by lack of a true pylome, by the number and arrangement of radial rods, as well as by the construction of the meshwork" (translation, Norris and Sarjeant, 1965, p. 16). As recounted by Sarjeant (1985), such care was taken by Wetzel (1933) in his original description of *C. utinensis* that subsequent workers had no difficulty in identifying the

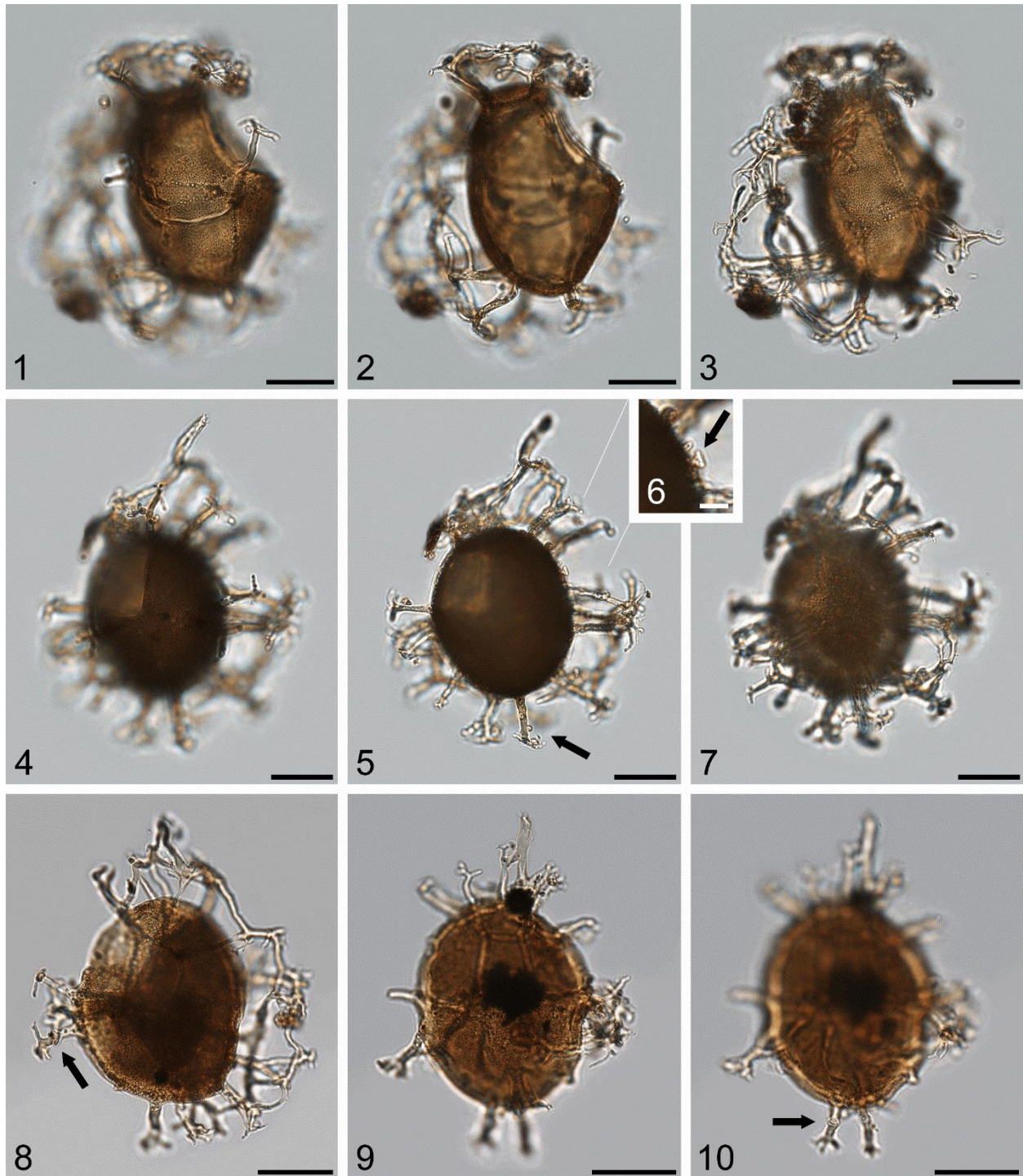


Plate 3.4. Bright-field photomicrographs of *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov. specimens. Oyster Bay Formation section abbreviations: AW = Appian Way. 1–3, holotype RBCM P1564, LN 45 m, Sample 54 (UVic 18-182, slide B, EF: G33/3), scale bars = 20 μ m; 1, left lateral view, major vesicles demarcating plate boundaries in focus; 2, left lateral view, autophragm wall thickness at mid-focus; 3, right lateral view, major vesicles demarcating plate boundaries and slender trabeculae in

focus. 4–7, paratype, AW 3.6 m, Sample 60 (UVic 18-179, slide A, EF: K41/0); 4, right dorsolateral view with autophragm surface and archaeopyle margin at 3''–4'' plate boundary in focus, scale bar = 20 µm; 5, mid-focus, note internal and external vesicles along the 3'''–1'''–4''' triple junction process (arrow), scale bar = 20 µm; 6, enlarged view of capitate vesicular protuberance on ventral surface (arrow), scale bar = 5 µm; 7, left ventrolateral view, autophragm surface and trabeculae in focus, scale bar = 20 µm. 8, paratype, AW base, Sample 57 (UVic 18-231, slide B, EF: D37/3), right lateral view, note distension of 3'''–4c–4''' triple junction process margin at midpoint due to large vesicle (arrow), scale bar = 20 µm. 9, 10, paratype, AW base, Sample 57 (UVic 18-231, slide B, EF: L43/1), scale bars = 20 µm; 9, dorsal view, surface of cingular region in focus; 10, mid-focus, note distension of 2'''–1'''–3''' triple junction process margin at midpoint due to large vesicle (arrow) and underdeveloped trabecular network.

species. A full synonymy of 244 identified records assignable to each of the seven species recognized at present has been compiled in Appendix 2.C.

Williams and Downie (1966, p. 222) proposed the first emendation to *Cannosphaeropsis* as to encompass spiniferate forms with “branching or furcate processes like those of *Hystrichosphaera* in both structure and distribution, but without sutural ridges or septa connecting their bases”. Williams and Downie (1966) further suggested that the genus be restricted to species possessing gonial and sutural processes in association with a precingular archaeopyle. Duxbury (1980, p. 114) expanded the diagnosis of the genus to include detail of the ectophragm as a “network of solid trabeculae” and emphasized the gonial positioning of projections either in the form of “spines” on the trabeculae or “rare” processes which connect the autophragm and ectophragm. The most recent emendation, provided by Marheinecke (1992, p. 41), states that processes arise only from the polar regions. While this is an observation pertinent to *Cannosphaeropsis utinensis* as indicated in the specific emendation of May (1980, p. 45), it cannot be applied to the genus as whole let alone any other species.

Cannosphaeropsis australis Riding and Helby, 2001 apparently lacks any ectophragmal processes supports altogether with the trabecular network effectively enclosing a free-floating autophragm while the proximochorate *Cannosphaeropsis hughesii* Harding, 1990 bears processes along all sutural boundaries in support of its low-relief rod-like trabeculae in comparison. In *Cannosphaeropsis franciscana*, processes are developed largely from plate triple junctions from all but the ventral sulcal series. In *Cannosphaeropsis passio* de Verteuil and

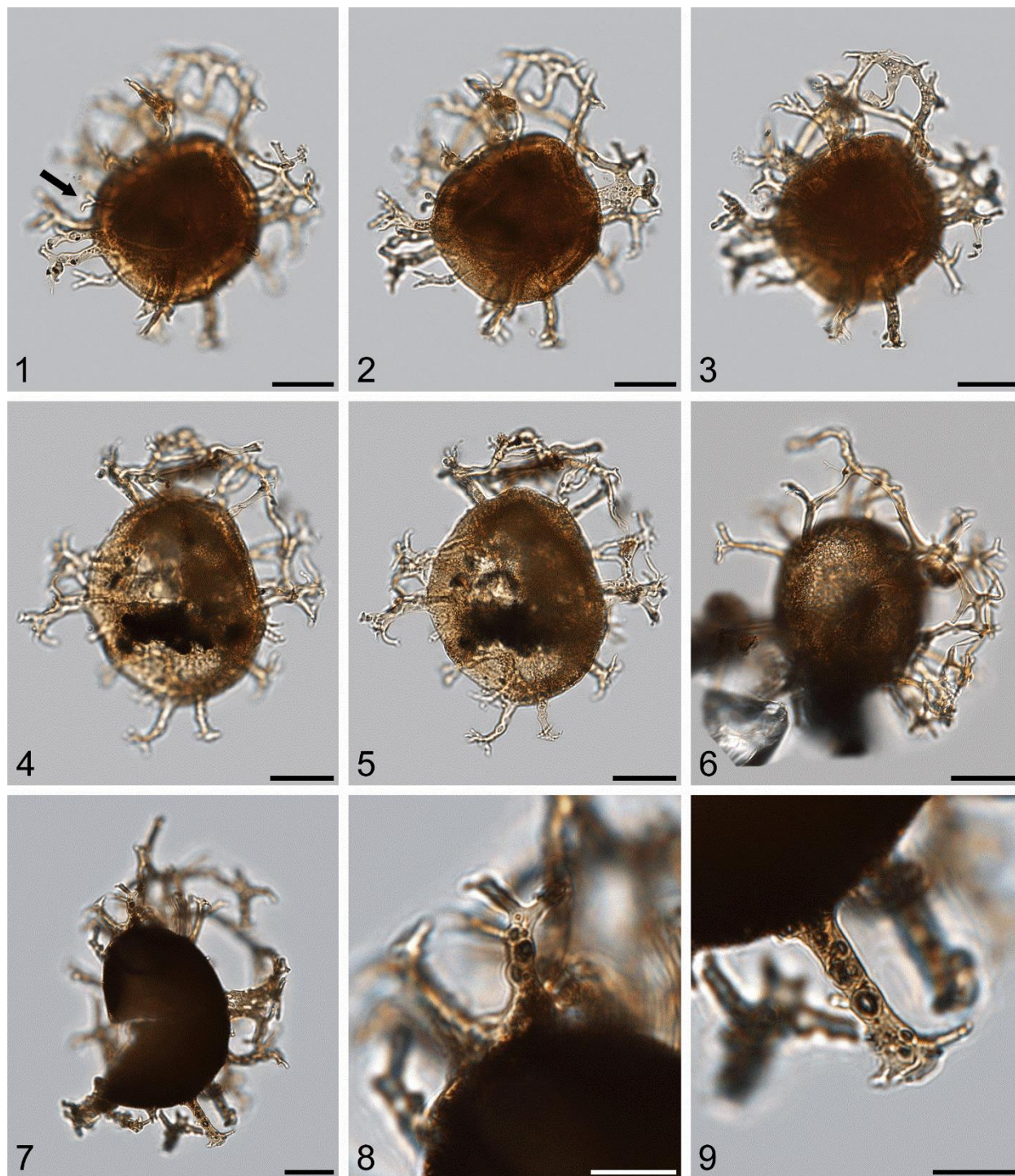


Plate 3.5. Bright-field photomicrographs of *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov. specimens. Oyster Bay Formation section abbreviation: AW = Appian Way. 1–3, holotype RBCM P1565, AW 1.3 m, Sample 58 (UVic 18-181, slide C, EF: R37/3), scale bars = 20 μ m; 1, right dorsolateral view, intergonal process arising from the 2''–3'' plate contact with bifid distal termination (arrow) and attached operculum in focus; 2, mid-focus, note robust, densely vesiculate lateral processes and trabecular

junction; 3, left ventrolateral view, trabeculae and inverted apical horn in focus. 4, 5, paratype, AW 1.3 m, Sample 58 (UVic 18-181, slide C, EF: N38/3), scale bars = 20 μm ; 4, right dorsolateral view, archaeopyle in focus; 5, mid-focus. 6, paratype, AW 1.3 m, Sample 60 (UVic 18-179, slide A, EF: J37/0), autophragm surface and trabeculae in focus, scale bar = 20 μm . 7–9, paratype, AW 1.3 m, Sample 60 (UVic 19-41, slide A, EF: V35/2); 7, right lateral view, note densely vesiculate, darkened autophragm, scale bar = 20 μm ; 8, dense vesiculation throughout 3''–3'–4'' triple junction process, scale bar = 10 μm ; 9, dense vesiculation throughout 3'''–1'''–4''' triple junction process, scale bar = 10 μm .

Norris, 1996, thin processes stem from the cingular equatorial region to support gracile trabeculae. In *Cannosphaeropsis quattrocchia* Guerstein et al., 2001, the ectophragm is supported by two process each arising from the dorsal anterior of the epicyst and the dorsal posterior of the hypocyst. Although some uncertainty surrounds the ectophragm reflected tabulation, *Cannosphaeropsis williamsii* Sarjeant, 1986 appears to possess processes which are both gonial and sutural without restriction.

A number of taxa have been questionably attributed to *Cannosphaeropsis* but remain problematic due to limited specimens, morphological ambiguity, or inadequate descriptions as to warrant their definitive inclusion in the genus. ?*Cannosphaeropsis densa* Cookson and Eisenack, 1962 and ?*Cannosphaeropsis scaffold*i (Baksi, 1962) Downie and Sarjeant, 1965 exhibit such trabecular density that tabulation is neither observed by the authors or discernible from the figured material. Similar density of serrate, subdivided, almost membranous, ribbon-like trabeculae obscures any surface features of ?*Cannosphaeropsis hyperacantha* Cookson and Eisenack, 1960, although the archaeopyle is visible. ?*Cannosphaeropsis glabra* Cookson and Eisenack, 1974 appears to have ribbon-like trabeculae joining less densely distributed processes, although insufficient detail is provided lending to archaeopyle position or to otherwise justify clear distinction from *Nematosphaeropsis*. ?*Cannosphaeropsis praetexta* Corradini, 1973 has irregularly distributed processes that may be basally and distally fenestrate with multifurcate terminations joined by thin, echinate trabeculae forming an irregular lace-like mesh. Both high-density of processes and inconsistency in their expression places ?*C. praetexta* in contrast with the typical gonial and sutural morphology characteristic of established species in the genus. ?*Cannosphaeropsis pulchra* Alberti, 1961 bears intermittent ribbon-like trabeculae which join

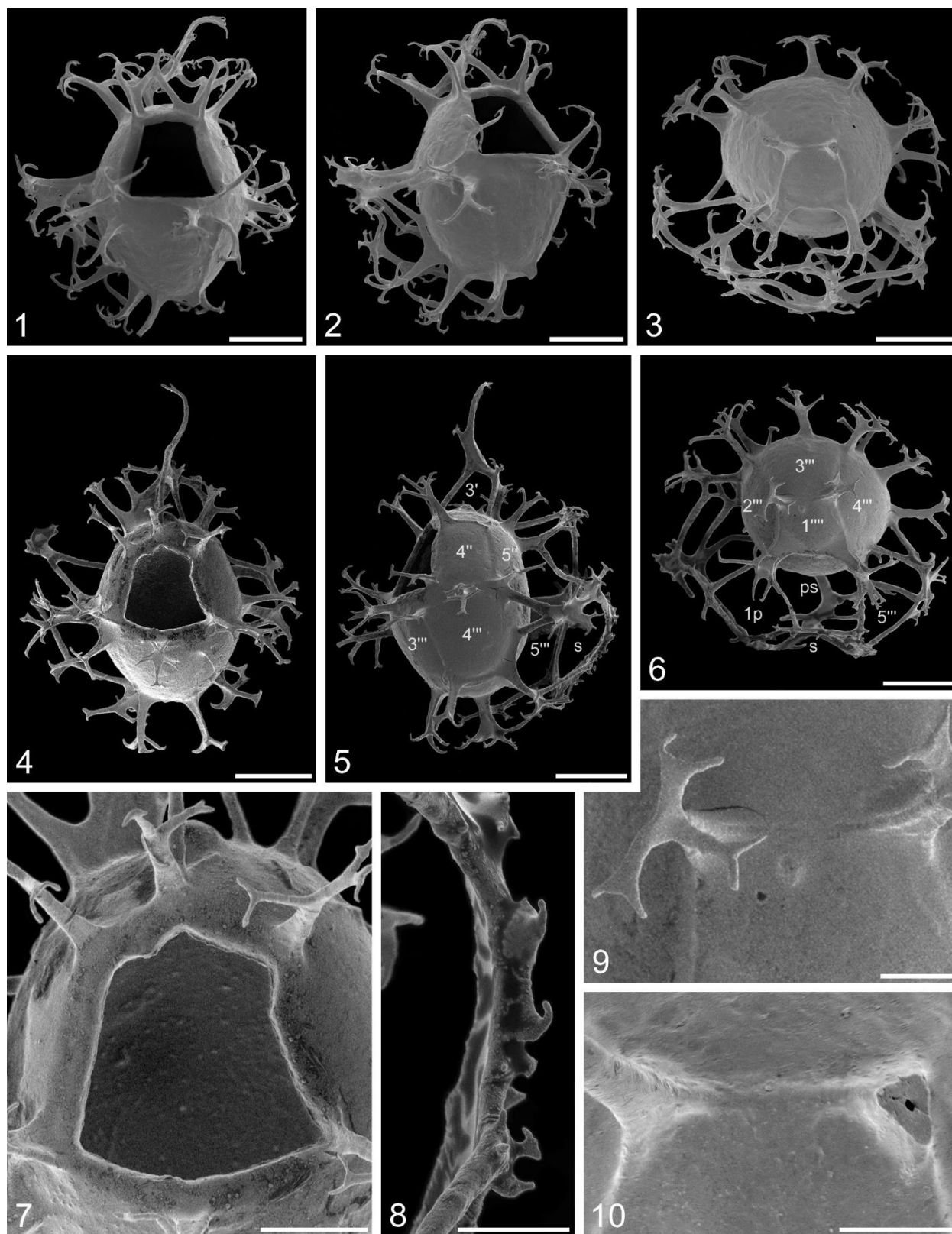


Plate 3.6. Scanning electron micrographs of *Cannosphaeropsis franciscana* subsp. *franciscana* specimens from the lower Appian Way section, Oyster Bay Formation. 1–3, 10, plesiotype with ramosus-type

processes, 3.6 m, Sample 60 (specimen P.1.01); 1, dorsal view, note septal ridge at 3'''–4''' contact, scale bar = 20 µm; 2, left dorsolateral view, scale bar = 20 µm; 3, antapical view, note septal ridges bordering antapical plate 1''', scale bar = 20 µm; 10, stem cross-section of 3'''–1'''–4''' triple junction process, scale bar = 5 µm. 4–9, plesiotype with ramosus-/septentrionalis-type processes, 6.6 m, Sample 62 (specimen A.C.03); 4, dorsal view, note curved apical horn, scale bar = 20 µm; 5, right lateral view with inferred tabulation, scale bar = 20 µm; 6, antapical view with inferred tabulation, note process stem skeletal rods and pronounced septal ridges bordering antapical plate 1''', scale bar = 20 µm; 7, enlarged view of archaeopyle margin and autophragm ventral interior surface texture, scale bar = 10 µm; 8, enlarged view of ventral trabecular ring serrate margin, scale bar = 5 µm; 9, enlarged view of 2'''–1'''–3''' triple junction distal process termination and septal ridges along 1''' contacts, note process skeletal rods, scale bar = 10 µm.

distally flared funnel-like processes. No surface features are described by Alberti (1961) and it may be referable to *Adnatosphaeridium* as noted by Stover and Evitt (1978).

Cannosphaeropsis franciscana Damassa, 1979

Cannosphaeropsis franciscana subsp. ***franciscana*** (autonym)

Plate 3.1, figs. 1–10; Plate 3.2, figs. 1–9; Plate 3.3, figs. 1–10; Plate 3.6, figs. 1–10; Plate 3.7, figs. 1–9; Plate 3.8, figs. 1–8; Fig. 3.3; Fig. 3.4A–C, F, G.

1967 *Cannosphaeropsis filifera* (Cookson and Eisenack, 1958) Cookson and Eisenack, 1960 | Drugg, p. 25, 26, pl. 4, fig. 16 [early Paleocene (Danian), California].

1979 *Cannosphaeropsis franciscana* Damassa, p. 204, 205, pl. 4, fig. 9, pl. 5, figs. 1–11 [early Paleocene (Danian), California].

2011 *Cannosphaeropsis fransisca* [sic] (Damassa); Slimani, Louwye, Duser, Lagrou, table 1, appendix A [Late Cretaceous (late Maastrichtian)–early Paleocene (late Danian), Belgium].

2021 *Cannosphaeropsis franciscana* (Damassa) McLachlan and Pospelova, fig. 5M, appendices A, B [Late Cretaceous (latest Maastrichtian)–early Paleocene (earliest Selandian), Vancouver Island, British Columbia].

Holotype: The holotype is UCLA specimen 58135, Sample 4764 from the Danian of the Franciscan Complex, California (Plate 3.1, figs. 1–3) housed within the Department of Earth and Space Sciences Paleontological Collection, University of California, Los Angeles (Damassa,

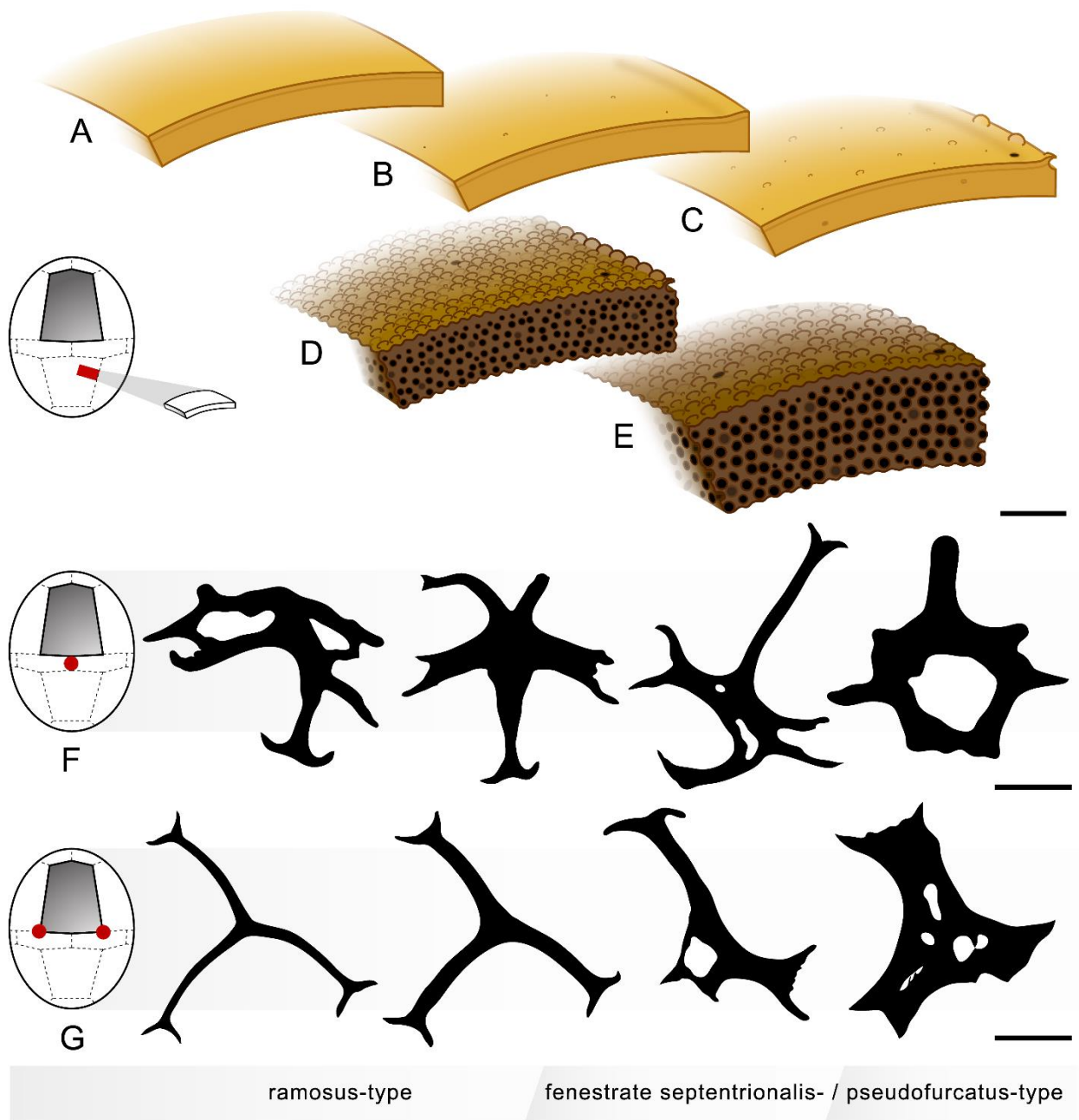


Figure 3.4. Schematic diagrams illustrating examples of distal process morphology and wall structure within the *Cannosphaeropsis franciscana* plexus. A–E, autophragm cross-sections and surface ornamentation, scale bar = 2 μ m. A, C. *f.* subsp. *franciscana*, solid structure and smooth surface. B, C. *f.* subsp. *franciscana*, solid structure, sparse microgranulate surface with raised septal ridges. C, C. *f.* subsp.

franciscana, solid structure, sparse microgranulate to granulate surface and isolated microfoveolations with raised septal ridges and sutural vesicle beading. D, *C. f.* subsp. *vacuoseptata* subsp. nov., nonuniform vesiculate structure, uneven undulate and sparsely microfoveolate surface with raised septal ridges bearing prominent vesicles. E, *C. f.* subsp. *vesiculata* subsp. nov., nonuniform vesiculate structure, uneven undulate to sparsely microfoveolate surface with plate margins devoid of septae. F, distal process terminations exhibited in the mid-dorsal process arising from the triple junctions 3c–3''–4c and 3c–4'''–4c across the 3c–4c contact, scale bar = 5 μm . G, distal process terminations exhibited in the dorsal gonial processes arising from the 2''–3c–3'' and 3''–4c–4'' triple junctions, scale bar = 5 μm . Process types after Londeix et al. (2018).

1979); autophragm length: 61.7 μm , autophragm width: 49.2 μm , ectophragm length: 146.9 μm , ectophragm width: 111.5 μm . 2'''–1''''–3'''/3'''–1''''–4''' process medial thickness: 2.1 μm . Holotype measurements extrapolated from the photomicrographs provided by Damassa (1979) and their respective magnifications and should therefore be considered imprecise.

Paratypes: UCLA specimens 58136, 58137, 58138, 58139, 58140, 58141, Sample 4764 from the Danian of the Franciscan Complex, California (Damassa, 1979), and the specimen originally figured by Drugg (1967, pl. 4, fig. 16) and re-illustrated by Damassa (1979, pl. 5, figs. 8, 9) from the Danian of the Moreno Formation, California (Plate 3.2, fig. 9). UCLA 58139, autophragm length (L_1): 50.6 μm , autophragm width (W_1) 40.2 μm , ectophragm length (L_2): 109.4 μm , ectophragm width (W_2): 95.2 μm , 2'''–1''''–3'''/3'''–1''''–4''' process medial thickness (T_2): 2.8 μm , lateral trabecular medial thickness (T_3): 1.9 μm . UCLA 58140, L_1 : 51.9 μm , L_2 : 115.6 μm , T_2 : 3 μm , T_3 : 2.7 μm . UCLA 58141, W_1 : 41.4 μm , W_2 : 90.4 μm , T_3 : 2.5 μm . Specimen of Drugg (1967) re-illustrated by Damassa (1979), L_1 : 67 μm , W_1 : 58 μm , L_2 : 126 μm , W_2 : 95 μm , T_2 : 4 μm , T_3 : 3 μm . Paratype measurements, if not given, are herein extrapolated from the photomicrographs provided by Damassa (1979) and their respective magnifications and should therefore be considered imprecise.

Plesiotypes: All from the Oyster Bay Formation, Vancouver Island, British Columbia. Plate 3.1, figs. 4, 5; Plate 3.3, fig. 8, AW 21.8 m, Sample 78; autophragm length (L_1): 58.4 μm , autophragm width (W_1) 44.4 μm , autophragm thickness (T_1): 1 μm , ectophragm length (L_2): 119.2 μm , ectophragm width (W_2): 89.2 μm , 2'''–1''''–3'''/3'''–1''''–4''' process medial thickness (T_2): 2.8 μm , lateral trabecular medial thickness (T_3): 3.2 μm . Plate 3.3, figs. 6, 7, AW 13.5 m,

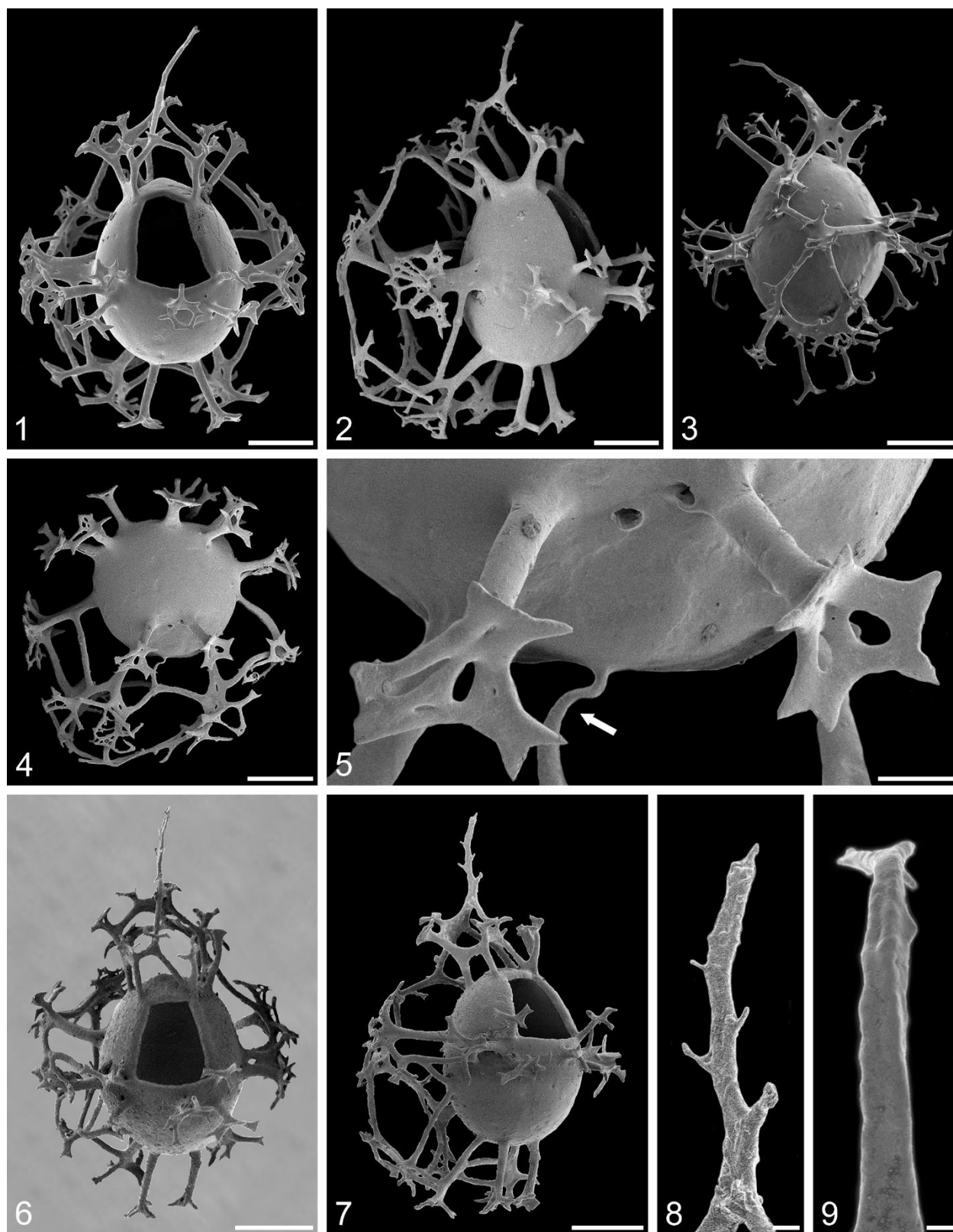


Plate 3.7. Scanning electron micrographs of *Cannosphaeropsis franciscana* subsp. *franciscana* specimens from the lower Appian Way section, Oyster Bay Formation. 1, 2, 4, 5, plesiotype with fenestrate

pseudofurcatus-type processes, 6.6 m, Sample 62 (specimen A.C.04); 1, dorsal view, scale bar = 20 μm ; 2, left lateral view, scale bar = 20 μm ; 4, dorsoantapical view, scale bar = 20 μm ; 5, enlarged view of distal process terminations and minute intergonal process (arrow), note isolated pores on autophragm surface and at base of 3'''–1''''–4''' triple junction process, scale bar = 10 μm . 3, plesiotype, 6.6 m, Sample 62 (specimen A.C.02), ventral view of teardrop-shaped trabecular ring, scale bar = 20 μm . 6–8, plesiotype with blunt ramosus-type processes, 6.6 m, Sample 62 (specimen C.C.01); 6, dorsal view, scale bar = 20 μm ; 7, left dorsolateral view, scale bar = 20 μm ; 8, enlarged view of acuminate apical horn, note disjunct barb-like tendrils along its length, scale bar = 2 μm . 9, plesiotype with ramosus-/septentrionalis-type processes, 6.6 m, Sample 62 (specimen A.C.03) enlarged right lateral view of apical horn, note trifurcate termination, scale bar = 1 μm .

Sample 68; L₁: 59.6 μm , W₁: 48 μm , T₁: 0.8 μm , L₂: 110.5 μm , W₂: 95.7 μm , T₂: 2 μm , T₃: 2.4 μm . Plate 3.1, figs. 8–10; Plate 3.3, figs. 9, 10, OR 2.3 m, Sample 90; L₁: 64.5 μm , W₁: 51.5 μm , T₁: 1.4 μm , L₂: 133 μm , W₂: 121 μm , T₂: 3.5 μm , T₃: 3.2 μm . Plate 3.2, figs. 1, 2, LN 3.1 m, Sample 21; L₁: 54.9 μm , W₁: 40.9 μm , T₁: 1 μm , L₂: 113.5 μm , W₂: 90.8 μm , T₂: 1.8 μm , T₃: 3.2 μm . Plate 3.2, fig. 3, LN 45 m, Sample 54; L₁: 58.8 μm , W₁: 47 μm , T₁: 1 μm , L₂: 88.8 μm , W₂: 93 μm , T₂: 2.4 μm , T₃: 1.8 μm . Plate 3.2, figs. 4–6, LN 3.1 m, Sample 21; L₁: 61.7 μm , T₁: 1 μm , L₂: 116.8 μm , T₂: 2.5 μm , T₃: 2 μm . Plate 3.2, fig. 7, AW 1.3 m, Sample 58; L₁: 49.3 μm , W₁: 42.4 μm , T₁: 1 μm , L₂: 100.1 μm , W₂: 80.1 μm , T₂: 2.2 μm , T₃: 2 μm . Plate 3.2, fig. 8, AW 1.3 m, Sample 58; L₁: 56.4 μm , W₁: 52.9 μm , T₁: 0.8 μm , L₂: 103.4 μm , W₂: 89.9 μm , T₂: 3.2 μm , T₃: 3.6 μm . Plate 3.3, fig. 1, AW 31.5 m, Sample 86; L₁: 53.7 μm , W₁: 43.2 μm , T₁: 1.1 μm , L₂: 86.8 μm , W₂: 79.1 μm , T₂: 2 μm , T₃: 1.8 μm . Plate 3.3, figs. 2–4, AW 31.5 m, Sample 86; L₁: 51.1 μm , W₁: 52.7 μm , T₁: 1.1 μm , L₂: 82.1 μm , W₂: 110.5 μm , T₂: 1.4 μm , T₃: 1.6 μm . Plate 3.3, figs. 5–7, AW 31.5 m, Sample 86; L₁: 49.5 μm , W₁: 44.6 μm , T₁: 0.8 μm , L₂: 93.4 μm , W₂: 74.2 μm , T₂: 1.6 μm , T₃: 1.2 μm . Plate 3.6, figs. 1–3, 10, AW 3.6 m, Sample 60; L₁: 54.4 μm , W₁: 43.3 μm , L₂: 88.8 μm , W₂: 77.5 μm , T₂: 2.2 μm , T₃: 1.9 μm . Plate 3.6, figs. 4–9, Plate 3.7, fig. 9, AW 6.6 m, Sample 62; L₁: 53.4 μm , W₁: 42 μm , L₂: 103.2 μm , W₂: 82.1 μm , T₂: 2.3 μm , T₃: 1.8 μm . Plate 3.7, figs. 1, 2, 4, 5, AW 6.6 m, Sample 62; L₁: 58.7 μm , W₁: 46 μm , L₂: 127.6 μm , W₂: 89.9 μm , T₂: 2.9 μm , T₃: 2.7 μm . Plate 3.7, fig. 3, AW 6.6 m, Sample 62; L₁: 52.9 μm , W₁: 43.1 μm , L₂: 103.6 μm , W₂: 77.3 μm , T₂: 2 μm , T₃: 2.4 μm . . Plate 3.7, figs. 6–8, AW 6.6 m, Sample 62; L₁: 47.5 μm , W₁: 37.9 μm , L₂: 106.8 μm , W₂: 69.9 μm , T₂: 2.7 μm , T₃: 2.8 μm . Plate 3.8, figs. 1–3, AW 3.6 m, Sample 60; L₁: 66.8 μm , W₁: 44 μm , L₂: 114.3 μm , W₂: 96.8 μm , T₂: 2.7 μm , T₃: 2

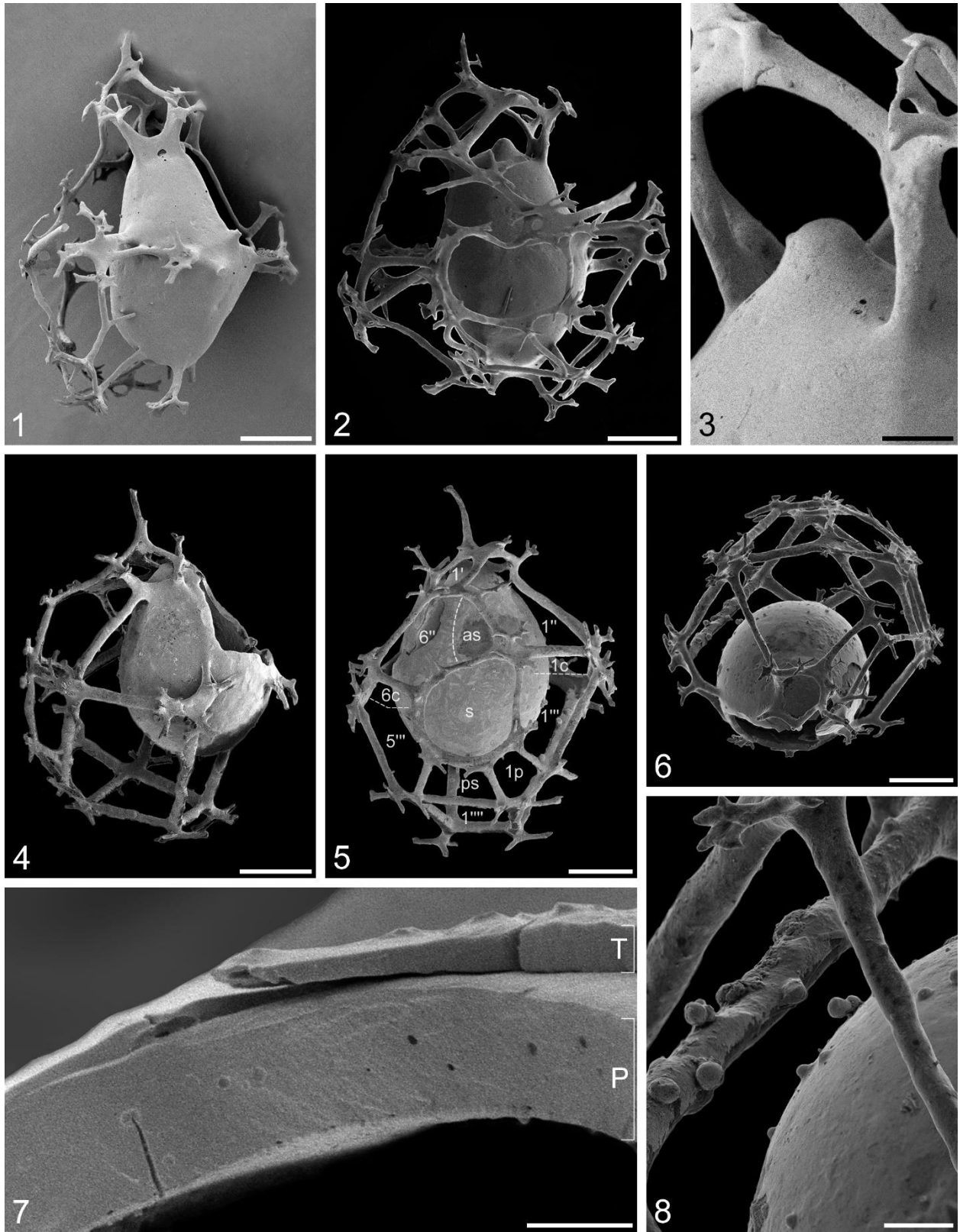


Plate 3.8. Scanning electron micrographs of *Cannosphaeropsis franciscana* subsp. *franciscana* specimens from the lower Appian Way section, Oyster Bay Formation. 1–3, plesiotype with elongate subhexagonal

central body ambitus and fenestrate pseudofurcatus-type processes, 3.6 m, Sample 60 (specimen 1.1.04); 1, left lateral view, scale bar = 20 μm ; 2, ventral view of semi-collapsed trabecular ring, scale bar = 20 μm ; 3, enlarged view of prominent apical boss and scattered foveolations, scale bar = 5 μm . 4–6, 8, plesiotype with pseudofurcatus-type processes and robust, vesiculate trabeculae, 6.6 m, Sample 62 (specimen A.C.01); 4, left lateral view, scale bar = 20 μm ; 5, ventral view of trabecular ring with inferred tabulation, scale bar = 20 μm ; 6, apical view, scale bar = 20 μm ; 8, enlarged view of vesicles along robust ventrolateral trabeculum and scattered erupted vesicles along ventrolateral autophragm surface, scale bar = 5 μm ; 7, plesiotype, 6.6 m, Sample 62 (specimen X.1.01), autophragm cross-section with exfoliation of pedium (P) and tegillum (T) of varying thickness, note sparse, minute pedial vesicles, scale bar = 1 μm .

μm . Plate 3.8, figs. 4–6, 8, AW 6.6 m, Sample 62; L₁: 64 μm , W₁: 49.8 μm , T₁: 1 μm , L₂: 118.6 μm , W₂: 84.7 μm , T₃: 3.2 μm . Plate VIII, 7, AW 6.6 m, Sample 62; T₁: 1.5 μm .

Emended diagnosis: A subspecies of *Cannosphaeropsis franciscana* with a subspherical to elongate subhexagonal central body ambitus; autophragm structure simple; surface smooth to sparsely microgranulate, undulate. Processes typically gonial; distal terminations gracile trifurcate and secondarily bifurcate to fenestrate multifurcate, lamellar trifurcate, fenestrate petaloid. Dorsal processes devoid of trabecular connections. Apical horn projecting from pole at point of trabecular convergence. Archaeopyle isosceles trapezoidal to subpentagonal, precingular, with formula P₃′, usually operculum free.

Emended description: Central body ambitus subspherical to elongate subhexagonal; autophragm structure is simple with the wall ranging from ~0.5–1.5 μm in total thickness comprised of an inner pedium and outer tegillum, the latter of which ranges from ~0.1–0.5 μm in thickness or ~10–30% the thickness of the former. The tegillum external surface is generally smooth but may occasionally present as sparsely microgranulate with low-relief undulations (Fig. 3.4A–C; Plate 3.8, fig. 7). An apical boss may be present in ellipsoidal to elongate hexagonal forms (Plate 3.6, fig. 7, Plate 3.8, figs. 2, 3). Vesicles are generally rare and occur infrequently if at all present; of 72 measured specimens, 8.3% exhibit linear sutural beading from septal vesicles and 9.7% are observed to have process vesicles. If present within the autophragm, vesicles are isolated within the pedium (Plate 3.8, fig. 7) or take the form of scattered protuberances on the ventral surface (Plate 3.8, figs. 6, 8). Vesicles may also occur in a pattern of sutural beading in alignment along dorsolateral plate margins (Fig. 3.4C; Plate 3.2, figs. 1, 3, 4).

If present internally within a process or trabeculum, vesicles are rarely developed to an extent as to distend the structural margin (Plate 3.1, fig. 6), although outlying examples exist where slight distention is evident within processes (Plate 3.2, fig. 5). Trabecular vesicles may also occur in small clusters at points along the exterior surface (Plate 3.8, fig. 8). Fenestrations at the base of processes are common while pores and perforate foveolations on the autophragm surface occur infrequently (Plate 3.7, fig. 5). Septal ridges are uncommon, but if present, subdued, joining processes (Plate 3.6, figs. 1–3, 5, 6, 9, 10). Processes typically gonial, but rare intergonials occur (Plate 3.7, fig. 5); stems minutely hollow, circular to triangular in cross-section with rounded to moderately concave sides; concave if processes supported by skeletal rods (Plate 3.6, figs. 6, 9). Dorsal, dorsolateral, and antapical process terminations range from gracile trifurcations with secondary bifurcations to fenestrate multifurcate or lamellar trifurcations forming a petaloid shape with fenestrations (Fig. 3.4F, G; see ramosus-, septentrionalis- and pseudofurcatus-type processes in Londeix et al., 2018). The ectophragm consists of a trabecular network joining apical, lateral and ventrolateral processes with a structure ranging from robust and expansive with angular trabecular junctions (Plate I, figs. 8–10; Plate VIII, figs. 4–6) to slender and diminutive (Plate 3.3, figs. 5–7; Plate 3.6, figs. 2, 3; Plate 3.7, fig. 3). The ectophragm is generally longer than wide reflecting an incomplete gonyaulacoid tabulation with the inferred formula $3'-6''-as-6c-s-5'''-ps-1p-1''''$ (Fig. 3.3). Processes arising from plates $2''$, $4''$, $3c$, $4c$, $2'''-4'''$, and the dorsal margin of plate $1''''$ are devoid of trabecular connections with adjacent dorsal processes. In rare instances, trabeculae are absent between all lateral processes (Plate 3.7, fig. 3). The midventral surface is devoid of processes and the perimeter of central sulcal plate (s) is reflected by a trabecular enclosure forming a ring or teardrop shape of varying expansion or contraction in the absence of deformation (Plate 3.2, fig. 2; Plate 3.7, fig. 3; Plate 3.8, fig. 5) which exhibits a serrate margin (Plate 3.6, fig. 8). An apical horn projecting from the point of polar trabecular convergence is a prominent feature typically extending 20–30 μm in length when well developed and not bent back against the ectophragm. The surface of the apical horn may bear minute tendrils or lobes (Plate 3.7, fig. 8; Damassa, 1979, pl. 5, fig. 7) with an acuminate, truncate, or more uncommonly, furcate termination (Plate 3.7, fig. 9). Coloration commonly yellow ochre, ranging from pale amber to golden bronze depending on wall thickness.

Dimensions: Autophragm length: 39.3 (54.5) 72.8 μm , number of specimens: 69; Damassa (1979): 57 (63) 73, number of specimens: 11; holotype: 61.7 μm . Autophragm width: 32.2 (42.7)

53.9 μm , number of specimens: 70; Damassa (1979): 40 (50) 59, number of specimens: 11; holotype: 49.2 μm . Autophragm thickness: 0.8 (1.1) 1.5 μm , number of specimens: 65. Ectophragm length: 64.5 (103.9) 144.8 μm , number of specimens: 69; Damassa (1979): 135 (153) 175, number of specimens: 11; holotype: 146.9 μm . Ectophragm width: 52.9 (79.4) 121 μm , number of specimens: 69; Damassa (1979): 89 (109) 140, number of specimens: 11; holotype: 111.5 μm . 2'''–1'''–3'''/3'''–1'''–4''' process medial thickness: 1.2 (2.6) 5 μm ; number of specimens: 72, holotype: 2.1 μm . Lateral trabecular medial thickness: 0.8 (2.4) 5.1 μm , number of specimens: 72. Holotype measurements were extrapolated from the photomicrographs provided by Damassa (1979) and their respective magnifications and should therefore be considered imprecise.

Range: *Cannosphaeropsis franciscana* subsp. *franciscana* ranges from the latest Maastrichtian to earliest Selandian within the Oyster Bay Formation, Vancouver Island, British Columbia. Rare specimens are observed in Sample 21 of Zone D1 and while the subspecies is absent in Zone D2, it occurs within every productive sample recovered throughout overlying zones D3–D5. The subspecies is also known from strata of Danian age within the Moreno Formation (Drugg, 1967, as *Cannosphaeropsis filifera* (Cookson and Eisenack) Cookson and Eisenack, 1960) and the Coastal Belt of the Franciscan Complex (Damassa, 1979), California. The only other record is that from an unillustrated report of the species spanning the late Maastrichtian–late Danian across the K/Pg boundary interval within the Chalk Group of northern Belgium (Slimani et al., 2011).

Remarks: The incomplete gonyaulacoid tabulation of *Cannosphaeropsis franciscana* subsp. *franciscana* is similar to that shared by several extant species of *Hafniasphaera*, *Nematosphaeropsis* and *Spiniferites* (e.g., Price and Pospelova, 2014; Wall, 1967). A number of these taxa, such as *Hafniasphaera multisphaerus* (Price and Pospelova, 2014) Londeix et al., 2018 and *Spiniferites bentorii* (Rossignol, 1964) Wall and Dale, 1970, exhibit an apical boss which is generally an uncommon feature among the specimens of *C. franciscana* examined from the Oyster Bay Formation. An apical boss is similarly expressed in the occasionally cavate modern *Hiddenocysta matsuokae* Gurdebeke et al., 2020 which is also presumed to possess a tripartite apical plate series. Specimens of *Cannosphaeropsis passio* known from middle Miocene strata are the only other species within the genus known to possess an apical boss (e.g.,

Engel, 1992, pl. 6, fig. 6; de Verteuil and Norris, 1996, pl. 17, figs. 1, 7 *redux* Head and Wrenn, 1992, pl. 10, fig. 1).

Drawing from a sample size of 11, Damassa (1979) recorded specimens of *Cannosphaeropsis franciscana* subsp. *franciscana* with ectophragm dimensions ranging up to 17% beyond those recorded in this study following “standard palynological techniques” (p. 192). It remains a possibility that an alternate sample preparation procedure could account for these morphometric discrepancies as different chemical treatments and mounting media used in the study of marine palynomorphs have been shown to yield variations in observed pollen grain size (e.g., Sluyter, 1997; Meltsov et al., 2008). From the material examined herein, no specimens were present in the $>120\ \mu\text{m}$ sieved fractions retained from any samples, indicating that no potentially larger specimens were overlooked or excluded.

***Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov.**

Plate 3.4, figs. 1–10; Plate 3.9, figs. 1–10, Plate 3.10, figs. 1–8; Plate 3.11, figs. 1–3; Fig. 3.3; Fig. 3.4D, F, G.

Etymology: From the French word *vacuole*, stemming from the Latin *vacuus* meaning “empty” and from *septum* meaning “partition” or “enclosure” in reference to both the vesiculate wall structure and septae defining plate boundaries.

Holotype: Specimen RBCM P1564 from Sample 54 (UVic 18-182, slide B, EF: G33/3), LN 45 m, UTM Grid Reference 343213E, 5531813N, Zone 10U; WGS84 and Dinoflagellate Cyst Zone D3 (Danian) of the Oyster Bay Formation, Vancouver Island, British Columbia, Canada. The specimen is housed within the paleontological collections of the Royal British Columbia Museum, Victoria, British Columbia. Plate 3.4, figs. 1–3, autophragm length: $62.4\ \mu\text{m}$, autophragm width: $44.1\ \mu\text{m}$, autophragm thickness: $2.6\ \mu\text{m}$, ectophragm length: $91.4\ \mu\text{m}$, ectophragm width: $80.5\ \mu\text{m}$, 2'''–1'''–3''' process medial thickness: $2.2\ \mu\text{m}$, lateral trabecular medial thickness: $2.4\ \mu\text{m}$.

Paratypes: All from the Appian Way section of the Oyster Bay Formation, Vancouver Island, British Columbia. Plate 3.4, figs. 4–7, 3.6 m, Sample 60; autophragm length (L_1): $54.1\ \mu\text{m}$, autophragm width (W_1): $45.2\ \mu\text{m}$, ectophragm length (L_2): $105.4\ \mu\text{m}$, ectophragm width (W_2):

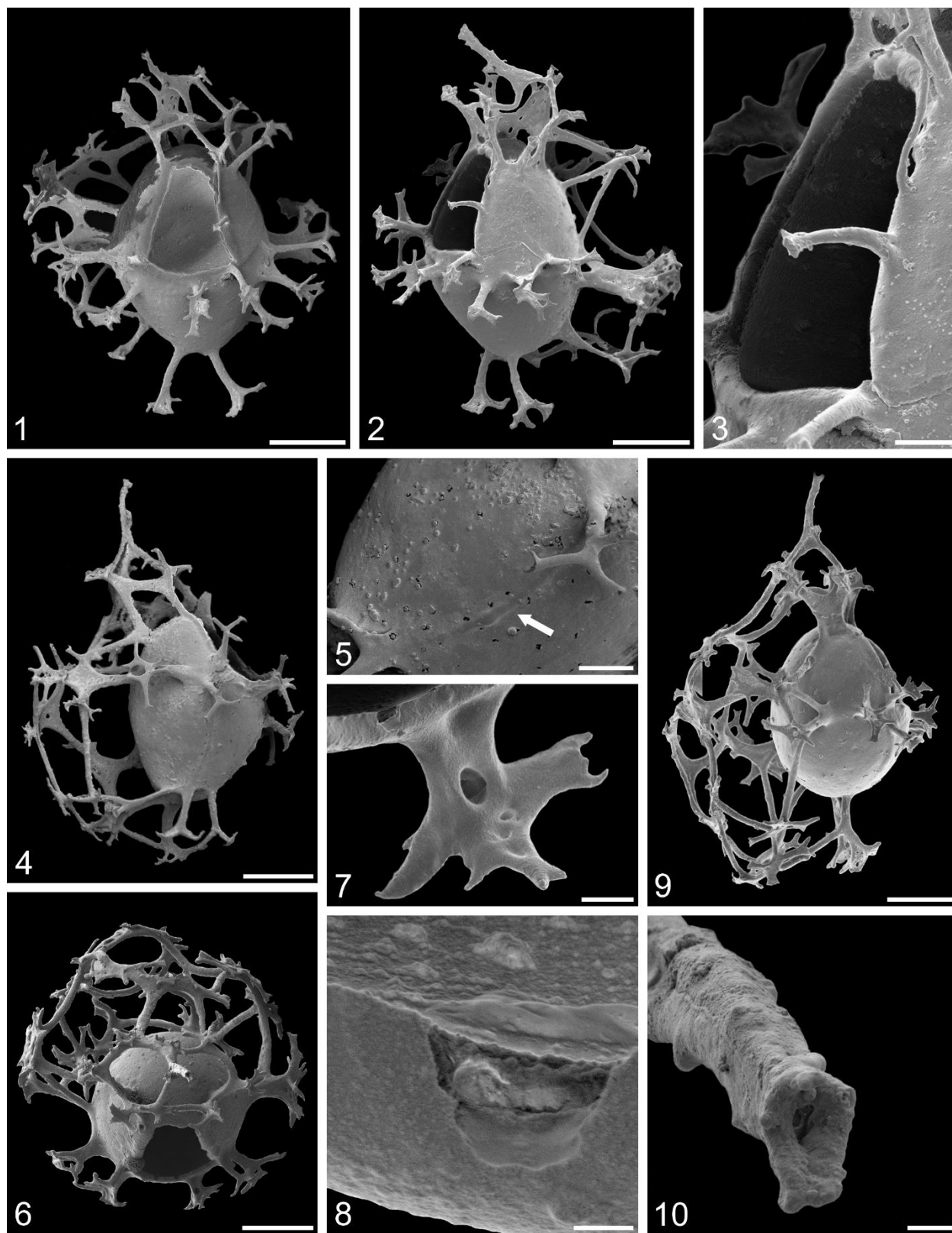


Plate 3.9. Scanning electron micrographs of *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov. specimens from the lower Appian Way section, Oyster Bay Formation. 1–3, paratype with

septentrionalis-type processes, 3.6 m, Sample 60 (specimen B.T.04); 1, dorsal view, scale bar = 20 μm ; 2, right lateral view, note aberrant trabeculum partly fused with autophragm along the 4''–5'' contact (arrow) and perforate ectophragmal membrane within the apical region trabecular network, scale bar = 20 μm ; 3, enlarged view of dual intergonal processes arising from the archaeopyle margin midway along 3''–4'' boundary, scale bar = 5 μm . 4, 5, paratype with blunt ramosus-type processes, 3.6 m, Sample 60 (specimen B.S.04); 4, left lateral view, note robust fusion platforms at trabecular junctions, scale bar = 20 μm ; 5, enlarged view of prominent vesiculate septal ridge along 2'''–3''' boundary (arrow), scale bar = 5 μm . 6–10, paratype with fenestrate pseudofurcatus-type processes, 3.6 m, Sample 60 (specimen B.S.05); 6, apical view, scale bar = 20 μm ; 7, enlarged view of archaeopyle margin along 3c–4c boundary and fenestrate stem of mid-dorsal process arising from the triple junctions 3c–3''–4c and 3c–3'''–4c across the 3c–4c contact, scale bar = 5 μm ; 8, enlarged view of autophragm surface exfoliation exposing underlying vesiculate wall structure, scale bar = 0.5 μm . 9, left lateral view, scale bar = 20 μm ; 10, enlarged view of truncate apical horn terminus, scale bar = 1 μm .

83.5 μm , 2''–1'''–3'''/3'''–1'''–4''' process medial thickness (T_2): 3.2 μm , lateral trabecular medial thickness (T_3): 2.2 μm . Plate 3.4, fig. 8, section base, Sample 57; L_1 : 54.9 μm , W_1 : 44.4 μm , autophragm thickness (T_1): 2.6 μm , L_2 : 88.4 μm , W_2 : 75.4 μm , T_2 : 3.5 μm , T_3 : 1.4 μm . Plate 3.4, figs. 9, 10, section base, Sample 57; L_1 : 49.9 μm , W_1 : 40.9 μm , T_1 : 1.8 μm , L_2 : 81.9 μm , W_2 : 62 μm , T_2 : 3 μm , T_3 : 1.6 μm . Plate 3.9, figs. 1–3, 3.6 m, Sample 60; L_1 : 54.6 μm , W_1 : 41.2 μm , L_2 : 96.8 μm , W_2 : 81.8 μm , T_2 : 2.4 μm , T_3 : 2.4 μm . Plate 3.9, figs. 4, 5, 3.6 m, Sample 60; L_1 : 54 μm , L_2 : 112.4 μm , T_2 : 2.1 μm , T_3 : 1.9 μm . Plate 3.9, figs. 6–10, 3.6 m, Sample 60; L_1 : 52.5 μm , W_1 : 42.7 μm , T_1 : 1.6 μm , L_2 : 126.7 μm , W_2 : 73.2 μm , T_2 : 2.1 μm , T_3 : 2.9 μm . Plate 3.10, figs. 1, 2, 4, 6.6 m, Sample 62; L_1 : 58.5 μm , W_1 : 42.9 μm , L_2 : 101.7 μm , W_2 : 75.8 μm , T_2 : 2.2 μm , T_3 : 2.3 μm . Plate 3.10, fig. 3, 3.6 m, Sample 60; L_1 : 53.3 μm , W_1 : 43.4 μm , L_2 : 106.2 μm , W_2 : 76.4 μm , T_2 : 2.3 μm , T_3 : 2.5 μm . Plate 3.10, figs. 5–8, Plate 3.11, figs. 1–3, 6.6 m, Sample 62; L_1 : 54.3 μm , W_1 : 46.8 μm , T_1 : 2.6 μm , L_2 : 91.8 μm , W_2 : 74.9 μm , T_2 : 2.2 μm , T_3 : 2.8 μm .

Diagnosis: A subspecies of *Cannosphaeropsis franciscana* with a subspherical to elongate subhexagonal central body ambitus; autophragm structure vesiculate, surface microgranulate to undulate, microfoveolate. Septal vesicles larger than those densely distributed elsewhere throughout the autophragm, reflecting the tabulation in their alignment along plate margins. Septal ridges present due to autophragm vesicular distention. Archaeopyle isosceles trapezoidal to subpentagonal, precingular, with formula P_3'' , usually operculum free.

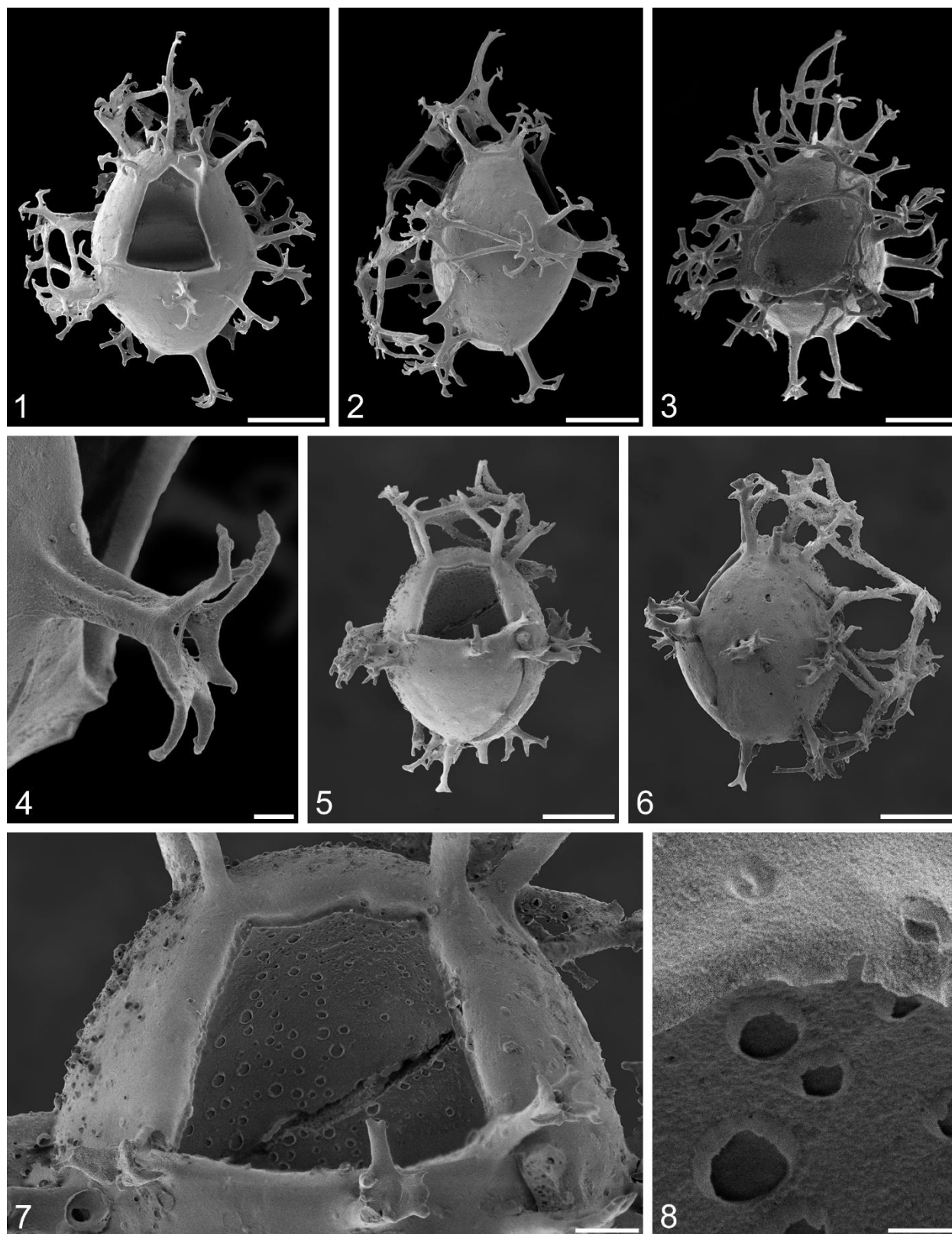


Plate 3.10. Scanning electron micrographs of *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov. specimens from the lower Appian Way section, Oyster Bay Formation. 1, 2, 4, paratype with

septentrionalis-type processes, 6.6 m, Sample 62 (specimen A.S.02); 1, dorsal view, scale bar = 20 μm ; 2, left lateral view, scale bar = 20 μm ; 4, enlarged view of skeletal rods along stem of multifurcate mid-dorsal process arising from the triple junctions 3c–3''–4c and 3c–3'''–4c across the 3c–4c contact, scale bar = 2 μm . 3, paratype, 3.6 m, Sample 60 (specimen B.S.03), ventral view of trabecular ring, scale bar = 20 μm . 5–8, paratype with blunt, underdeveloped processes, 6.6 m, Sample 62 (specimen A.S.01); 5, dorsal view, scale bar = 20 μm ; 6, right lateral view, scale bar = 20 μm ; 7, enlarged view of archaeopyle, note erupted, calderic vesicles across the central body lateral margins and ventral interior surface, scale bar = 5 μm ; 8, enlarged view of 2'–3''–3' triple junction region, note erupted, calderic vesicles at archaeopyle margin and across the ventral autophragm interior surface, scale bar = 1 μm .

Description: General morphology as for autonym with the following exceptions: Autophragm structure is vesiculate with the wall ranging from ~ 1.5 –3 μm in total thickness comprised of a fused inner pedium and outer tegillum, the latter of which is distinguished by a reduced density of vesicles and ranges from ~ 0.2 –0.3 μm in thickness or ~ 10 –15% the thickness of the pedium (Fig. 3.4D; Plate 3.11, fig. 3). The tegillum external surface is microgranulate to undulate, microfoveolate (Plate 3.9, fig. 8; Plate 3.11, fig. 3). Septal vesicles are well-developed (up to 1.5 μm in diameter), larger than those densely distributed throughout the autophragm (typically < 0.5 μm in diameter) and in alignment along the length of plate boundaries forming raised ridges (Fig. 3.4D; holotype, Plate 3.4, figs. 1, 3; paratype, Plate 3.4, figs. 8, 9; paratype, Plate 3.9, figs. 4, 5). Intratabular vesicles often give the superficial appearance of coarse granulation through transmitted light microscopy. Processes are typically gonal with rare intergonals which, if present, generally occur along the archaeopyle margin and may arise asymmetrically along plate boundaries (Plate 3.9, figs. 2, 3). Processes and trabeculae with intermittent vesicles (Plate 3.11, fig. 2), rarely transecting the process as to distend its margins in profile (Plate 3.4, figs. 8, 10). Erupted vesicles, if present, are more prevalent on the processes as well as lateral to ventral regions of the central body (Plate 3.4, fig. 5; Plate 3.10, fig. 7; Plate 3.11, figs. 1, 2). Autophragm is light brown to golden brown in color depending on wall thickness.

Dimensions: Autophragm length: 42.2 (54.1) 64.9 μm ; holotype: 62.4 μm ; number of specimens: 25. Autophragm width: 35.5 (42.7) 51.7 μm ; holotype: 44.1 μm ; number of specimens: 22. Autophragm thickness: 1.5 (2.3) 2.8 μm ; holotype: 2.6 μm ; number of specimens: 20. Ectophragm length: 67.5 (94.7) 132.2 μm ; holotype: 91.4 μm ; number of specimens: 25.

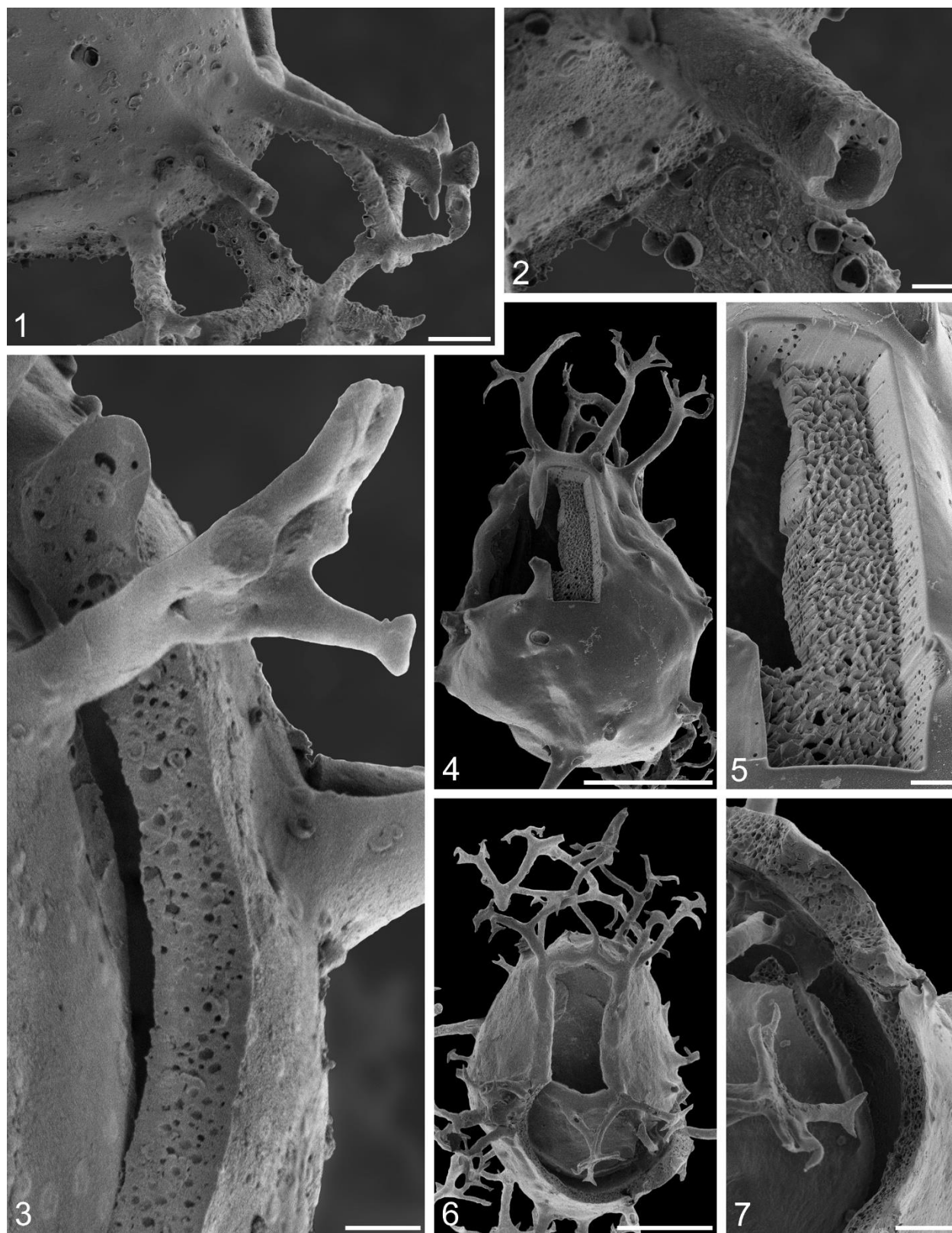


Plate 3.11. Scanning electron micrographs of *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov. and *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov. specimens from the lower Appian

Way section, Oyster Bay Formation. 1–3, *C. f.* subsp. *vacuoseptata* subsp. nov. paratype with blunt, underdeveloped processes, 6.6 m, Sample 62 (specimen A.S.01); 1, right lateral view of autophragm surface, processes and trabeculae with erupted, calderic vesicles, scale bar = 5 μm ; 2, enlarged view of 3'–4''–5''' triple junction process in cross-section and erupted, calderic vesicles, scale bar = 1 μm ; 3, enlarged view of 3'''–4c–4''' triple junction process and cross-section of vesiculate autophragm displaced across longitudinal fracture near plate 4''' margin, scale bar = 2 μm . 4, 5, *C. f.* subsp. *vesiculata* subsp. nov. paratype, 3.6 m, Sample 60 (specimen Y.1.01); 4, right dorsolateral view with site of focused ion beam (FIB) ablation extending longitudinally across plate 4'', scale bar = 20 μm ; 5, enlarged view of FIB ablation site exposing dense vesiculation in the lower pedium, giving the appearance of an intricate reticulum, scale bar = 2 μm . 6, 7, *C. f.* subsp. *vesiculata* subsp. nov. paratype, 3.6 m, Sample 60 (specimen Y.1.02); 6, dorsal view with partly collapsed autophragm, scale bar = 20 μm ; 7, enlarged view of vesiculate autophragm cross-section at point of transverse fracture, note variability in wall thickness, scale bar = 4 μm .

Ectophragm width: 52.5 (72.4) 85.8 μm ; holotype: 80.5 μm ; number of specimens: 21. 2'''–1'''–3'''/3'''–1'''–4''' process medial thickness: 1.8 (2.4) 3.5 μm ; holotype: 2.2 μm ; number of specimens: 26. Lateral trabecular medial thickness: 1 (2) 2.9 μm ; holotype: 2.4 μm ; number of specimens: 25.

Range: *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov. ranges from Zone D3 to D4 (latest Maastrichtian–early Danian) of the Oyster Bay Formation, Vancouver Island, British Columbia; most prevalent in Zone D3 and the lowermost strata of Zone D4 with its highest occurrence marked by an isolated specimen recovered from the middle of subzone D4a.

Comparison: *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov. is distinguished from the type subspecies, *C. f.* subsp. *franciscana*, by its vesiculate autophragm and differs from *C. f.* subsp. *vesiculata* subsp. nov. in possessing septal vesicles which are typically larger than those densely distributed elsewhere throughout the autophragm. The larger septal vesicles of *C. f.* subsp. *vacuoseptata* subsp. nov. reflect the tabulation in their alignment along plate margins whereas tabulation in the latter subspecies is indiscernible. The autophragm of *C. f.* subsp. *vacuoseptata* subsp. nov. exhibits a thinner, less densely vesiculate wall in contrast with *C. f.* subsp. *vesiculata* subsp. nov., and it is typically smaller with more reduced processes and gracile trabeculate.

Remarks: *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov. (Plate 3.4, fig. 6) occasionally bears vesicular protuberances across the ventral surface which are analogous to the structures observed in *Cannosphaeropsis hughesii* Harding, 1990 described as “hemispherical intratabular tubercles” (Harding, 1990, pl. VI, 11, 12). Such features are also among the few manifestations of vesiculation which occur in isolated specimens of *Cannosphaeropsis franciscana* subsp. *franciscana* (Plate 3.8, figs. 6, 8), although they are typically much more sparsely distributed and reduced in the type subspecies.

***Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov.**

Plate 3.5, figs. 1–9; Plate 3.11, figs. 4–7; Plate 3.12, figs. 1–8; Fig. 3.3; Fig. 3.4E–G.

?1967 ?*Cannosphaeropsis* sp. B Drugg, p. 26, pl. 4, fig. 18 [early Paleocene (Danian), California].

Etymology: From the Latin *vesicula* meaning “little bladder” or “blister” in reference to the many bubble-like voids which characterize the densely vesiculate wall structure.

Holotype: Specimen RBCM P1565 from Sample 58 (UVic 18-181, slide C, EF: R37/3), AW 1.3 m, UTM Grid Reference 343882E, 5530750N, Zone 10U; WGS84 and Dinoflagellate Cyst Zone D3 (Danian) of the Oyster Bay Formation, Vancouver Island, British Columbia, Canada. The specimen is housed within the paleontological collections of the Royal British Columbia Museum, Victoria, British Columbia. Plate 3.5, figs. 1–3, autophragm length: 54.9 μm , autophragm width: 52.7 μm , autophragm thickness: 4.1 μm , ectophragm length: 94.9 μm , ectophragm width: 94.9 μm , 2'''–1'''–3''' process medial thickness: 3.4 μm , lateral trabecular medial thickness: 3 μm .

Paratypes: All from the Appian Way section of the Oyster Bay Formation, Vancouver Island, British Columbia. Plate 3.5, figs. 4, 5, 1.3 m, Sample 58; autophragm length (L_1): 67.1 μm , autophragm width (W_1): 55.7 μm , autophragm thickness (T_1): 4.2 μm , ectophragm length (L_2): 101.4 μm , ectophragm width (W_2): 94.9 μm , 2'''–1'''–3'''/3'''–1'''–4''' process medial thickness (T_2): 2.8 μm , lateral trabecular medial thickness (T_3): 3 μm . Plate 3.5, fig. 6, 1.3 m, Sample 60; L_1 : 52.7 μm , W_1 : 44 μm , T_1 : 3.4 μm , L_2 : 99.1 μm , W_2 : 87.8 μm , T_2 : 2 μm , T_3 : 1.6 μm . Plate 3.5, figs. 7–9, 1.3 m, Sample 60; T_2 : 3 μm , T_3 : 2.2 μm . Plate 3.11, figs. 4, 5, 3.6 m, Sample 60; L_1 : 49.9 μm , L_2 : 85.9 μm , T_2 : 2.4 μm . Plate 3.11, figs. 6, 7, 3.6 m, Sample 60; L_1 : 60.8 μm , T_1 : 2.7 μm , L_2 : 106.8 μm , T_2 : 2.3 μm , T_3 : 2.5 μm . Plate 3.12, figs. 1, 2, 3.6 m, Sample 60; T_1 : 3.2 μm .

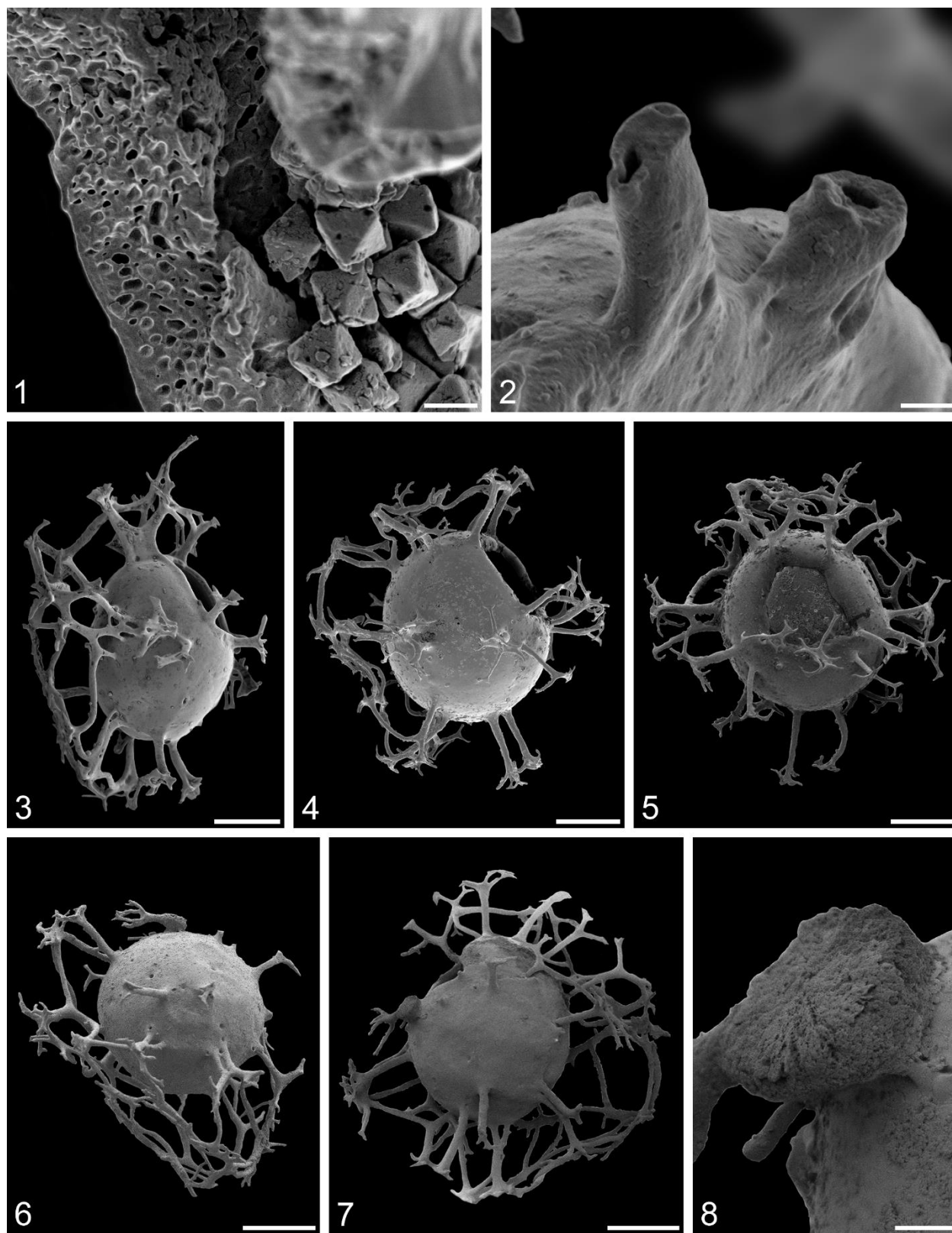


Plate 3.12. Scanning electron micrographs of *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov. specimens from the lower Appian Way section, Oyster Bay Formation. 1, 2, paratype, 3.6 m, Sample

60 (specimen C.T.02); 1, cross-section of densely vesiculate autophragm, note central body octahedral pyrite crystal infill, scale bar = 1 μm ; 2, enlarged view of vesiculate processes in cross-section along folded cingular(?) plate contact, scale bar = 1 μm . 3, paratype with fenestrate pseudofurcatus-type processes, 3.6 m, Sample 60 (specimen B.T.03), left lateral view, scale bar = 20 μm . 4, 5, paratype with septentrionalis-type processes, 3.6 m, Sample 60 (specimen B.S.02); 4, left lateral view, scale bar = 20 μm ; 5, dorsal view, scale bar = 20 μm . 6–8, paratype with underdeveloped, blunt ramosus-type processes, 3.6 m, Sample 60 (specimen B.S.01); 6, antapical view, note thin trabecular network, scale bar = 20 μm ; 7, right lateral view, scale bar = 20 μm ; 8, enlarged view of probable epiphytic marine fungus and pathological deformation of the mid-dorsal process arising from the triple junctions 3c–3''–4c and 3c–3'''–4c across the 3c–4c contact, scale bar = 2 μm .

Plate 3.12, fig. 3, 3.6 m, Sample 60; L₁: 52.7 μm , L₂: 116.7 μm , T₂: 3.2 μm , T₃: 2.1 μm . Plate 3.12, figs. 4, 5, 3.6 m, Sample 60; L₁: 57.8 μm , W₁: 53 μm , L₂: 103.2 μm , W₂: 97.2 μm , T₂: 2 μm , T₃: 1.9 μm . Plate XII, 6–8, 3.6 m, Sample 60; L₁: 53.8 μm , W₁: 52.6 μm , L₂: 96.1 μm , W₂: 90 μm , T₂: 2.4 μm , T₃: 1.9 μm .

Diagnosis: A subspecies of *Cannosphaeropsis franciscana* with a subspherical to ellipsoidal central body ambitus; autophragm structure densely vesiculate; surface microgranulate, undulate to microfoveolate. Processes typically gonial; distal terminations gracile trifurcate and secondarily bifurcate to lamellar trifurcate, fenestrate petaloid. Dorsal processes devoid of trabecular connections. Apical horn projecting from pole at point of trabecular convergence. Archaeopyle isosceles trapezoidal to subpentagonal, precingular, with formula P₃'', usually operculum free.

Description: General morphology as for autonym with the following exceptions: Central body ambitus subspherical to ellipsoidal; autophragm structure is vesiculate with the wall ranging from ~1.5–5 μm in total thickness comprised of a fused inner pedium and outer tegillum. The latter is distinguished by a reduced density of vesicles and ranges from ~0.2–0.3 μm in thickness or ~8% the thickness of the pedium (Fig. 3.4E; Plate 3.11, figs. 5, 7; Plate XII, 1). The tegillum external surface is microgranulate to undulate, microfoveolate with occasional erupted vesicles (Fig. 3.4E; Plate 3.12, fig. 2). Septal and intratabular vesicles are well-developed and usually of similar size (typically <0.5–1.5 μm in diameter), densely distributed throughout the autophragm. Plate boundaries are indiscernible beyond the archaeopyle margin. Processes are typically gonial

with rare intergonals which, if present, generally occur along a raised archaeopyle margin and may arise asymmetrically along plate boundaries (holotype: Plate 3.5, fig. 1). Processes and trabeculae bearing prevalent vesicles, frequently bulging their margins and distending their structure in profile (Plate 3.5, figs. 1, 5, 8, 9; Plate 3.11, fig. 2). Autophragm is dark brown to light brown in color depending on wall thickness.

Dimensions: Autophragm length: 49.9 (58.3) 67.1 μm ; holotype: 54.9 μm ; number of specimens: 20. Autophragm width: 41.3 (49.5) 57.6 μm ; holotype: 52.7 μm ; number of specimens: 20. Autophragm thickness: 3.2 (3.6) 4.3 μm ; holotype: 4.1 μm ; number of specimens: 18. Ectophragm length: 78.4 (98.8) 116.8 μm ; holotype: 94.9 μm ; number of specimens: 18. Ectophragm width: 61.2 (84.2) 103.8 μm ; holotype: 94.9 μm ; number of specimens: 20. 3'''–1'''–4'''/4'''–1'''–5''' process medial thickness: 1.6 (2.7) 4.1 μm ; holotype: 3.4 μm ; number of specimens: 24. Lateral trabecular medial thickness: 1 (2.1) 3.2 μm ; holotype: 3 μm ; number of specimens: 23.

Range: *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov. is constrained to within Zone D3 (latest Maastrichtian–earliest Danian) of the Oyster Bay Formation, Vancouver Island, British Columbia with one possible reported occurrence within the Danian of the Moreno Formation, California (Drugg, 1967).

Comparison: *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov. is distinguished from the type subspecies, *C. f.* subsp. *franciscana*, by its vesiculate autophragm and differs from *C. f.* subsp. *vacuoseptata* subsp. nov. in lacking discernible plate boundaries and possessing well-developed vesicles which are densely distributed throughout a generally thicker autophragm. The septal vesicles of *C. f.* subsp. *vacuoseptata* subsp. nov. are typically larger than those elsewhere within the autophragm and clearly reflect tabulation in alignment along plate margins. Cyst bodies of *C. f.* subsp. *vesiculata* subsp. nov. are also generally larger than those of *C. f.* subsp. *vacuoseptata* subsp. nov., exhibiting more robust processes and trabecular networks as well as greater prevalence of ectophragmal vesicles.

Remarks: Drugg (1967, p. 26) described his ?*Cannosphaeropsis* sp. B. from the Danian of the Moreno formation, California, noting the presence of a “conspicuously vacuolate” autophragm and trabecular connections “confined to one hemisphere” of the spherical central body. While not included in the written description, vesiculation is also evident in the processes and

trabeculae of the sole specimen figured by Drugg (1967, pl. 4, fig. 18). It is not clear from the photomicrograph if the region devoid of trabecular connections represents the dorsal surface of the specimen. Therefore, its relationship to similar forms belonging to the *Cannosphaeropsis franciscana* plexus observed from the Oyster Bay Formation cannot be definitively ascertained.

3.7 Discussion

3.7.1 Taxonomic implications

Spiniferate gonyaulacacean dinoflagellate cysts regarded as members of the *Spiniferites* group are herein defined as those species belonging to the acavate genera: *Achomosphaera*, *Cannosphaeropsis*, *Dalella*, *Evittosphaerula*, *Hafniasphaera*, *Nematosphaeropsis*, *Spiniferella*, *Spiniferites*, *Trabeculidium* and *Unipontidinium*. *Achomosphaera*, *Spiniferella* and *Spiniferites* comprise genera with freestanding processes while *Cannosphaeropsis*, *Dalella*, *Evittosphaerula*, *Nematosphaeropsis*, *Trabeculidium* and *Unipontidinium* consist of forms which possess ectophragms characterized by trabecular connections. Mertens and Carbonell-Moore (2018) provide a review of *Spiniferites* and a comparative discussion of related genera which have a complicated taxonomic history (Sarjeant, 1974). The *Spiniferites* group is host to a sizable portion of the fossil dinoflagellate cyst taxa retained at subspecific rank (see Fensome et al., 2019), many of which have been described from Upper Cretaceous–Paleocene deposits belonging to the genera *Achomosphaera* (Boltenhagen, 1977; Marheinecke, 1992), *Spiniferella* (He Chengquan, 1991; Slimani et al., 2012) and *Spiniferites* (de Wit, 1943; Wetzell, 1952; Davey and Williams, 1966; Corradini, 1973; Cookson and Eisenack, 1974; Hansen, 1977; Jain, 1978; Marheinecke, 1992; Schiøler, 1993; Slimani, 1996; Pearce, 2010). Hoyle et al. (2019) even proposed the adoption of variability matrices as an alternative approach to taxonomic subcategorization illustrating the challenges faced by workers given the considerable range of plasticity in spiniferate forms.

Hansen (1977) erected *Hafniasphaera* to encompass vesiculate cysts within the *Spiniferites* group which are predominantly present in the Late Cretaceous–early Paleogene fossil record. Evitt (1985) questioned the justification of generic level differentiation on the basis of vacuolate wall features in the same way Stover and Williams (1987) regarded *Hafniasphaera* to be a junior

synonym of *Spiniferites* arguing that its basic morphology is adequately accommodated within the latter genus. However, Edwards (1996) retained *Hafniasphaera* without explanation and this action was upheld by Williams et al. (1998) who also refrained from presenting a justification. Quattrocchio and Sarjeant (2003) proposed that *Hafniasphaera* be relegated to subgeneric status beneath *Spiniferites*. Fensome et al. (2009) acknowledged the theoretical merit of this move and the possibility of a continuum between the two genera, but noted questionable practicality in subgenus application given the variance in the degree of vesiculation between the autophragm and processes. Fensome et al. (2009) therefore provided an emendation to *Hafniasphaera* emphasizing process vesiculation over that exhibited in the central body.

Vesiculation among *Spiniferites* group taxa has generally been restricted to taxa within the genus *Hafniasphaera*; the only extant species being *H. multisphaerus* (Price and Pospelova, 2014). Londeix et al., 2018 described from modern and late Quaternary sediments collected in the Gulf of California (Price et al., 2013 as *Spiniferites* type 1; Price and Pospelova, 2014). Vesicles in the form of “blisters and hollow undulations” (Head, 2007, p. 1011) are apparently present in dense distribution—albeit at a far more diminutive scale—throughout the outer layer (tegillum) of the autophragm in *Spiniferites ristingensis* Head, 2007 recorded from Upper Pleistocene sediments in the Baltic region (Head et al., 2005 as *Spiniferites* sp. 1; Head, 2007). *Spiniferites ristingensis* is therefore the only formally proposed vesiculate non-trabeculate species retained outside of *Hafniasphaera* with the possible exception of ?*Achomosphaera granulata* from the Quaternary deposits of the South China Sea (Mao, 1989; Mao and Harland, 1993; see remarks in Mertens et al., 2018).

Precedent also exists for vesiculation in *Cannosphaeropsis*, which is a diagnostic trait in the Oligocene–Miocene species *Cannosphaeropsis passio* de Verteuil and Norris, 1996. In some early works, members of the species recovered from Miocene rocks were attributed to *Cannosphaeropsis utinensis sensu* Brown and Downie (1985). These specimens were described as exhibiting a “finely punctate to finely microreticulate” surface by Head and Wrenn (1992, p. 4) who noted a characteristic “finely microreticulate subsurface pattern” (1992, p. 22, pl. 9, figs. 6, 7). The presence of a “finely punctate endophragm” in the species was also reported by McCarthy and Mudie (1996, p. 255). When these forms were synonymized under *C. passio* by de Verteuil and Norris (1996, p. 132), the description was revised to one emphasizing a “pervasively alveolate endoblast and trabeculae”. De Verteuil and Norris (1996) adopted the

terminology of Below (1987) and employed the use of the term *alveoles* to describe structural voids ranging from $<0.2\text{--}0.4\text{ }\mu\text{m}$. Vesicles with a diameter of $<0.5\text{ }\mu\text{m}$ are known in species of *Hafniasphaera* (Hansen, 1977) and given their description of the wall layer relationships, the alveoles of de Verteuil and Norris (1996) are effectively minute vesicles.

A few informal spiniferate dinoflagellate cyst species presenting vesiculation have been attributed to *Cannosphaeropsis*, all from western North America. The “conspicuously vacuolate” ?*Cannosphaeropsis* sp. B of Drugg (1967, p. 26) from the Danian of the Moreno Formation, California, has been questionably assigned to *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov. in the present study. Also, Evitt (1973) described his *Cannosphaeropsis* aff. *utinensis* from the Maastrichtian Kemp Clay and Danian Kincaid Formation encompassing the K/Pg boundary interval near Waco, Texas. This form is noted as differing from the *C. utinensis* holotype in possessing a “thicker and finely granular” autophragm (Evitt 1973, p. 33). Aydin (2013) also reported the occurrence of this form in the uppermost Maastrichtian of the Corsicana Formation and lowermost Danian of the overlying Kemp Clay exposed along the Brazos River, Texas, which she designated her *Cannosphaeropsis* sp. 1, in so doing expanding the definition to include process and trabecular vesiculation.

Beyond wall structure and the presence of vesiculation, variance in process and ectophragm development has been observed which exceeds the conventional parameters used to establish members of the genus *Cannosphaeropsis*. Stover and Evitt (1978) and Wrenn (1988) present comparative remarks about the genera *Cannosphaeropsis* and *Nematosphaeropsis*. Wrenn (1988) emphasizes that the processes of the former are joined below furcate terminations by singular trabeculae whereas the tips of the process terminations of the latter are typically connected by pairs of trabeculae. Stover and Evitt (1978) also note the trabecular differentiation and both studies (Stover and Evitt, 1978; Wrenn, 1988) underscore the greater prevalence of septal ridges in *Nematosphaeropsis*. Van Mourik et al. (2001) recorded their intergeneric *Cannosphaeropsis/Nematosphaeropsis* spp. from Bartonian–Priabonian rocks offshore Florida as did Van Mourik and Brinkhuis (2005) from the Priabonian–lowermost Rupelian strata of central Italy. Guerstein et al. (2004) reported an intergradational specific form from the lower Miocene of the Centinela Formation, Argentina, which they assigned to their *Nematosphaeropsis/Cannosphaeropsis* sp. The species shares some minor similarities with *Cannosphaeropsis franciscana* such as a ventral area devoid of processes and dorsal processes

being the least developed in relation to those at either pole. However, singular ribbon-like trabeculae occur in association with cylindrical trabeculae linked to membranous distal process platforms (Guerstein et al., 2004, figs. 7a–f).

A range of conventionally specific level distinctions in *Spiniferites* taxa are exhibited in *Cannosphaeropsis franciscana* with respect to a plexus of ramosus-, septentrionalis- and pseudofurcatus-type process development (Fig. 3.4F, G; see descriptive overview in Londeix et al., 2018). It could be argued that distal process termination (DPT) morphology provides grounds for subspecific designation in *C. franciscana*. However, Damassa (1979) included the specimen figured by Drugg (1967, pl. 4, fig. 16) in her original *C. franciscana* type series which appears to have pseudofurcatus-type DPTs while providing an essentially ramosus-type DPT description for the species. It is the position of the authors of this study that wall structure, as a fundamental character, is of higher taxonomic significance and is thus the basis for the present subspecific distinction in the species with vesiculation also being among the most easily distinguished traits through light microscopy. Moreover, in the case of *C. franciscana*, these DPT forms are observed across the spectrum of vesiculation while co-occurring in the same assemblages.

3.7.2 Paleoenvironmental and paleoecological interpretations

Spiniferate members of the gonyaulacaceae, largely consisting of taxa belonging to the genera *Achomosphaera*, *Hafniasphaera* and *Spiniferites* in most assemblages, are often amalgamated into a *Spiniferites* group based on the inference of shared ecology as a tool for paleoenvironmental reconstructions in Late Cretaceous–early Paleogene studies (e.g., Frieling and Sluijs, 2018; Vellekoop et al., 2019; Chakir et al., 2020). Trabeculate species belonging to other closely related genera such as *Nematosphaeropsis* may also be incorporated, although these forms are considered to offer greater utility in presenting an offshore signal (e.g., Wall et al., 1977; Dale, 1996) while *Spiniferites*, for example, is more indicative of upper water column instability in otherwise well-stratified lower-energy settings with greater nutrient availability (Pospelova et al., 2018). There exist numerous instances of *Cannosphaeropsis* use in deriving paleoenvironmental interpretations stemming from its uncanny morphological analogy to modern species of *Nematosphaeropsis* which have an open marine to oceanic preference (e.g.,

Wall et al., 1977; Brinkhuis and Biffi, 1993). Both genera have been considered equivalent indicators of a similar habitat and, therefore, a shared paleoecological niche has been postulated resulting in the two genera occasionally being merged into their own *Nematosphaeropsis/Cannosphaeropsis* ecogroup (Brinkhuis, 1994; Van Mourik et al., 2001; Sluijs et al., 2005).

Specifically, *Cannosphaeropsis utinensis* was considered by Sarjeant (1985, p. 149) to be “an offshore form confined to warmer waters” and in the North Sea, it has been regarded as indicative of maximum flooding phases (Lund et al., 1993). This interpretation is bolstered by the co-occurrence of *Pterodinium* spp. and *C. utinensis* in high relative abundance in the Upper Cretaceous strata of northern Spain associated with deep offshore settings (Radmacher et al., 2020). Inversely, in the more recent fossil record, Besems (1993) observed a correlation between low numbers of *Impagidinium* and *Nematosphaeropsis* and similarly rare occurrences of *Cannosphaeropsis quattrocchiaie* (then *C. cf. utinensis*) in association with inner neritic paleoenvironments as evidenced by assemblages from the upper Neogene strata offshore Borneo. Parras et al. (2020) observed *C. quattrocchiaie* to be a mid- to outer shelf species in the same vein, noting its localized stratigraphic constraint at the height of the transgressive systems tract within the lower Miocene Punta Entrada Member of the Monte León Formation, Argentina, where its concentrations range from between ~50–150 cysts g⁻¹.

In light of the clear affinity of *Cannosphaeropsis* taxa with less restrictive marine settings, a more offshore preference for *Cannosphaeropsis franciscana* is supported by the marine palynological assemblage data from the Oyster Bay Formation. The most elevated *C. franciscana* cyst concentrations occur within Zone D3 (~1–361 cysts g⁻¹, avg. ~123 cysts g⁻¹) and subzone D4a (~20–370 cysts g⁻¹, avg. ~133 cysts g⁻¹) in association with the highest relative abundances of taxa belonging to the coastal *Cordosphaeridium* group and distally transported saccate pollen within intervals presumed to coincide with periods of sea level rise including that of the prominent global transgressive regime in the early Danian (e.g., Miller, 2009; Esmeray-Senlet et al., 2015; see McLachlan and Pospelova, 2021). Pyrite crystal infill is also a frequent occurrence among specimens recovered from Zone D3 and their octahedral shapes (Plate 3.12, fig. 1) indicate diagenetic formation under sulfur-rich suboxic or anoxic conditions likely related to processes of bacterial sulphate reduction in organic-rich sediments due to high primary productivity in the upper water column (e.g., Schoonen, 2004; Barnard and Russo, 2009).

3.7.3 Ecophenotypic expression

It is increasingly understood that a range of environmental factors influence gonyaulacacean dinoflagellate cyst morphology beyond the constraints of genetic determinism and members of the *Spiniferites* group have long been the focus of research which has provided grounds for the proposition of ecophenotypic expression (e.g., Wall et al., 1973; Harland, 1982, 1983). Work on modern taxa has established the effect of low salinity on endocyst geometry leading to a reduction in size (e.g., Ellegaard et al., 2002) and the development of a cruciform ambital profile (e.g., Wall et al., 1973; Mudie et al., 2018; Hoyle et al., 2019). Process length can reflect both salinity and temperature as shown among certain species cultured in laboratory settings (e.g., Ellegaard et al., 2002; Rochon et al., 2009) and recovered from the upper euphotic zone (e.g., Mertens et al., 2009a, 2012a; Verleye et al., 2012). Data from some studies, such as that conducted by Mertens et al. (2011) on *Protoceratium reticulatum*, present correlation between increased salinity and temperature values which also result in a correlation between sea-surface density and sea-surface salinity rendering it indeterminable which factor—or combination thereof—is the driver of greater process length. However, this relationship can be reversed in some environmental settings due to cryptic speciation (e.g., Mertens et al., 2012b; Gurdebeke et al., 2018; Wang et al., 2019). Recent investigations have also proposed nutrient availability as playing a key role in cyst formation and dimensions (e.g., Popescu et al., 2009; Mousing et al., 2017).

Ecophenotypy is far more difficult to demonstrate among extinct dinoflagellate cyst taxa in deep time records. Pre-Neogene instances are limited to such observations as underdeveloped ‘wing’ membranes in *Thalassiphora pelagica* as a possible function of deoxygenation (Pross, 2001) and distribution patterns among *Homotryblium* species suggestive of salinity determinant process length (Dybkjær, 2004). In broader terms, the macroevolutionary trend of dinoflagellate cyst body size reduction has been linked to declining nutrients and paleoclimatic shifts toward decreased global mean temperatures (Finkel et al., 2007). Guerstein et al. (2004) surmised that the intergeneric gradation within their *Nematosphaeropsis/Cannosphaeropsis* sp. from the lower Miocene of the Centinela Formation, Argentina, may reflect a response to paleoenvironmental

stresses resulting from changes in salinity, temperature or water depth. Indeed, modern laboratory encystment experiments involving motile *Gonyaulax spinifera* have produced intergrades between *Spiniferites* and *Nematosphaeropsis* cyst morphotypes under higher salinity conditions strongly suggesting not only an environmental trigger for trabecular development, but a close genetic relationship between the extant dinoflagellate cyst species *Spiniferites ramosus* and *Nematosphaeropsis labyrinthus* (Rochon et al., 2009). Additionally, similar *Spiniferites*–*Nematosphaeropsis* intergrades have also been documented in the basal Lynnwood section of the Oyster Bay Formation (McLachlan and Pospelova, 2021).

The gonyaulacacean fossil record sees vesiculation as most abundant within the genus *Hafniasphaera*. Forms attributable to *Hafniasphaera* had their greatest prevalence during the Late Cretaceous–early Paleogene with 35.4% of all illustrated reports constrained to within the Danian Stage and 62.3% from within the Paleocene Series overall (Fig. 3.5, Appendix 2.C). Reports of several species of *Hafniasphaera* (*H. cryptovesiculata*, *H. graciosa*, and *H. hyalospinosa*) are heavily concentrated in the Danian as well (e.g., Hansen, 1977; Dastas et al., 2014; Açıkalın et al., 2015) with *H. cryptovesiculata* recognized as a zonal indicator for the later portion of the stage in northern Europe (e.g., Hansen, 1977; Hultberg, 1985; Köthe, 1991). Further to the hypothesis of paleoenvironmentally-triggered morphotypes, it is also noteworthy that in more recent Quaternary sediments, *Spiniferites bentorii* and *Hafniasphaera multisphaerus* are of essentially identical morphology save for the presence of vesiculation in the latter. Their co-occurrence in the same samples (Price and Pospelova, 2014) suggest *H. multisphaerus* may be an ecophenotypic variant of *S. bentorii*.

Based on modern sediment trap studies (Pospelova et al., 2010; Price and Pospelova, 2011), dormancy time in general has been observed to be longer for gonyaulacacean cysts than for other extant taxa resulting in their development of elaborate processes that likely slow down their descent through the water column. We suggest that the development of vesicles that are likely filled with gas is the next step in the process of increasing cyst buoyancy prolonging their residency time in the upper water column. The ecology of *Hafniasphaera* also points in this direction. *Hafniasphaera* spp. have been interpreted as thermophilic due to their heightened abundances during times of inferred elevated sea-surface temperature such as the Paleocene-Eocene Thermal Maximum (PETM) (e.g., Frieling and Sluijs, 2018; Smith et al., 2021). A warmer climate regime would have been one circumstance supporting greater ocean stratification

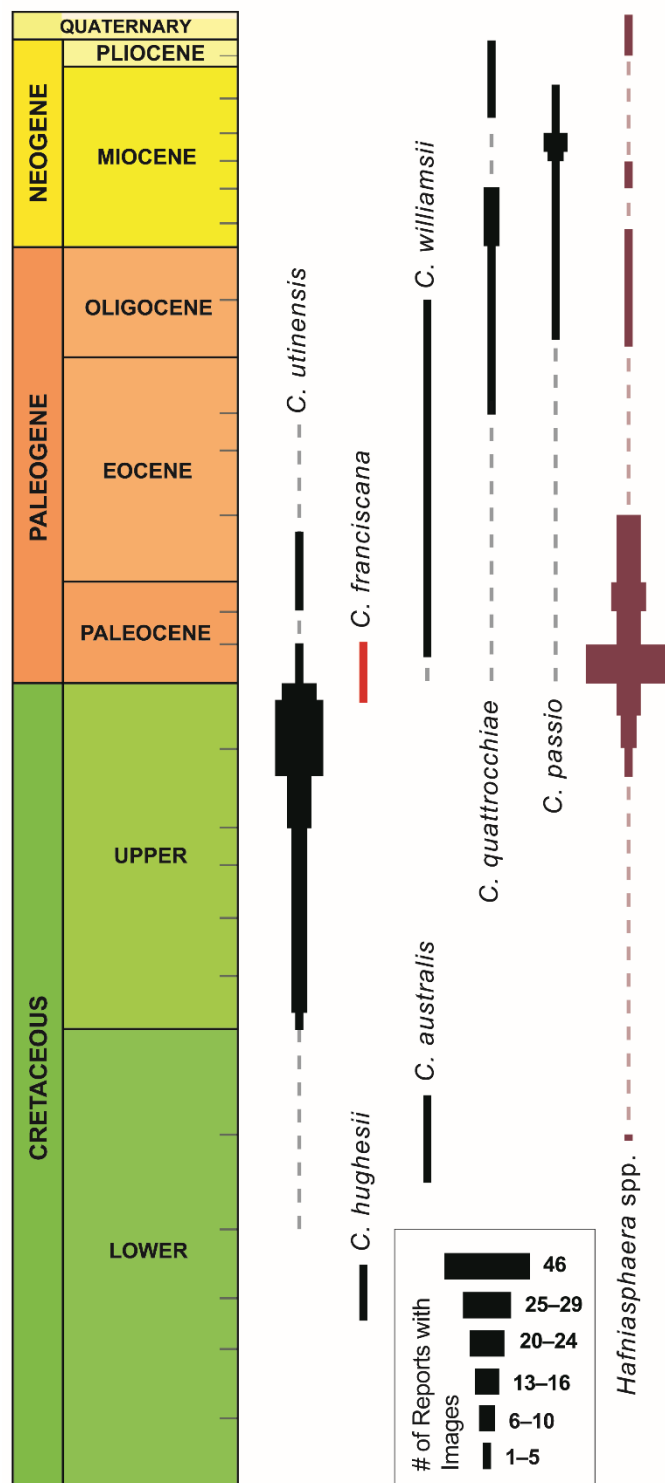


Figure 3.5. Chronostratigraphic distribution of the seven accepted species belonging to the genus *Cannosphaeropsis* following Fensome et al. (2019) and *Hafniasphaera* spp., based on reports in the peer-reviewed literature accompanied by photomicrographs. Stage-level resolution has been adopted in the

presentation of report density wherein local ranges are rounded to encompass the entirety of their corresponding stage(s) when higher resolution data is not available. Global range bases and tops have been plotted as precisely as possible. Dashed lines extending beyond the ranges derived from illustrated reports denote uncertainty due to unillustrated materials, possible reworking, or imprecise chronostratigraphic data. Range of *Cannosphaeropsis franciscana* highlighted in red.

and by extension, vesiculation may have been an adaptation to sustain cyst buoyancy under more stratified ocean conditions. Furthermore, the greater frequency of pyritization in the material from Zone D3 (Plate 3.12, fig. 1), when *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov., *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov., and *Hafniasphaera* spp. were found in high abundances, provides evidence of localized suboxic or anoxic bottom waters characteristic of a setting with a stratified water column.

It is readily observed that significant vesiculation in *Cannosphaeropsis franciscana*—as opposed to process furcation variance—is predominantly constrained to within Zone D3 of the Oyster Bay Formation, directly above the K/Pg boundary during a time of probable elevated marine instability during the onset of the early Danian transgressive phase. The ratio of *Hafniasphaera* spp. to *Spiniferites* spp. also increases notably over an order of magnitude from 1.34 in Zone D2 to 14.5 in Zone D3 with elevated cyst concentrations in the Danian beds (Fig. 3.6). The spectrum of vesicular intergradation within *C. franciscana* sees increased likelihood of causation originating from yet to be established exact paleoenvironmental factors, but is likely related to greater stratification of the water column. This interpretation is further reinforced by the presence of exclusively non-vesiculate forms at similar concentrations (>100 cysts g^{-1}) within comparable sample sizes obtained from the mid- to upper reaches of subzone D4a and lowermost subzone D4b exposed at the Appian Way locality where waters were likely shallower and better mixed (Fig. 3.2). It seems unlikely that ocean temperature alone could account for the development of vesicles in *C. franciscana* given the absence of *C. f.* subsp. *vacuoseptata* subsp. nov. and *C. f.* subsp. *vesiculata* subsp. nov. in the basal Lynnwood section when the species punctuates an otherwise prolonged absence with occurrence in the Sample 21 assemblage marked by the *Palynodinium grallator* acme (McLachlan and Pospelova, 2021), otherwise associated with a late Maastrichtian warming event (Vellekoop et al., 2019).

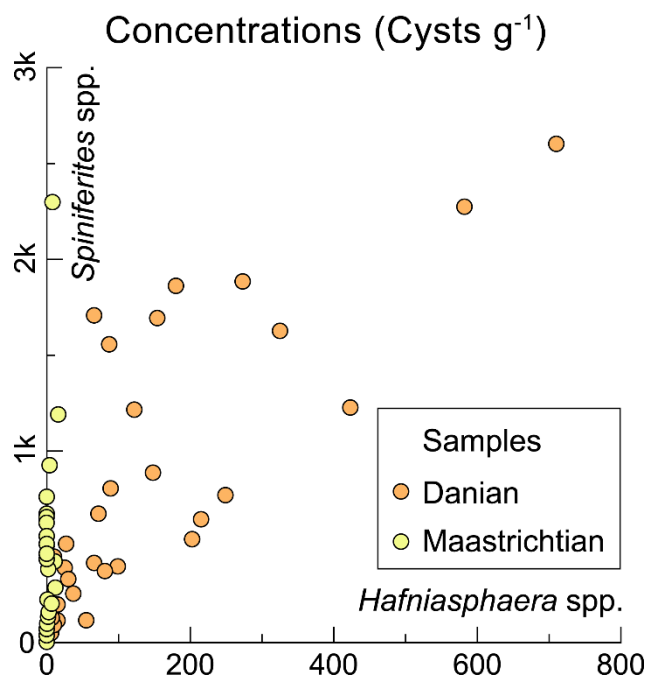


Figure 3.6. Cyst concentrations of *Hafniasphaera* spp. plotted against those of *Spiniferites* spp. in each studied sample, Oyster Bay Formation, Vancouver Island, British Columbia. Yellow points denote Maastrichtian samples. Orange points denote Danian samples.

It is intriguing that erupted and ‘burst’ calderic vesicles on the autophragm surface are most prevalent within the ventral–ventrolateral hemisphere as well as those of the processes and trabeculae located thereabouts in rare specimens of *C. f.* subsp. *franciscana* (Plate 3.8, fig. 8) and *C. f.* subsp. *vacuoseptata* subsp. nov. (Plate 3.4, fig. 6; Plate 3.10, fig. 8; Plate 3.11, fig. 1). This observation suggests that these erupted vesicles constitute a form of ecophenotypic expression occurring in concert with what might otherwise be construed as the more likely genetic parameters governing the cyst body plan wherein the same region sees the most advanced ectophragm development. This brings into question the extent to which more major structural features such as trabeculae might actually be reflective of environmental conditions as stands to be elucidated by further laboratory experimentation with consideration given to the aforementioned work of Rochon et al. (2009).

Vesiculate subspecies, including *C. f.* subsp. *vesiculata* subsp. nov. which exhibits the most extensive vesiculation and is restricted to Zone D3, also bear smaller central bodies, reduced processes, and slender trabecular connections compared to those typical of *C. f.* subsp.

franciscana. This is consistent with the findings of Ellegaard et al. (2002) wherein higher salinities (45 psu) resulted in shorter processes and smaller central bodies in the cysts of *Gonyaulax baltica*. Conversely, shortened processes in *Lingulodinium* spp. have been used as a low salinity proxy (e.g., Lewis and Hallett, 1997; Mertens et al., 2009a, 2012a), although endocyst and process reduction observed in *Gonyaulax baltica* experimentation is more applicable in this instance as the taxon constitutes the motile stage of the more analogous cyst species *Spiniferites bulloideus* (e.g., Lewis et al., 1999; Mertens and Carbonell-Moore, 2018).

At the opposite end of the salinity spectrum, a more elongate to cruciform endocyst is a feature that would be expected in a spiniferate species under more brackish conditions (e.g., Kouli et al., 2001; Mudie et al., 2001, 2018) which is less frequently the case among the vesiculate morphotypes. The most compact central body, seen in *C. f.* subsp. *vesiculata* subsp. nov., ranges from subspherical to ellipsoidal whereas *C. f.* subsp. *vacuoseptata* subsp. nov. and *C. f.* subsp. *franciscana* present end members with profiles approaching elongate subhexagonal (Plate 3.4, figs. 1–3; Plate 3.8, figs. 1, 2). Incidentally, vesiculate forms reach their zenith before the onset of elevated relative abundances and concentrations of marine constituents such as *Paralecaniella indentata*, *Exochosphaeridium phragmites*, *Senegalinium* spp. and *Xenikoon australis* near the base of Zone D4 which are regarded as low salinity-tolerant taxa if not directly associated with freshwater incursion (e.g., Heilmann-Clausen, 1985; Sluijs and Brinkhuis, 2009; Peyrot et al., 2012; see McLachlan and Pospelova, 2021). Increased temperatures have also been recognized as playing a role in cyst size reduction (Mousing et al., 2017) and a period of early Danian warming within the first 0.5 myr of the Paleocene has been well documented based on δO_{18} records (e.g., Zachos et al., 1989; Woelders et al., 2017). This suggests that while salinity and temperature may have influenced cyst geometry and process development in *C. franciscana*, they cannot be placed as sole stressors responsible for triggering vesiculation. Thus, local water column stratification caused by changes in sea-surface temperature and/or salinity in nutrient-rich waters is likely the triggering factor for vesiculation.

3.7.4 Biochronology

The Gonyaulacaceae has become the dominant family of cyst-forming dinoflagellates since their Bajocian radiation shortly after the appearance of these forms during the Early Jurassic (e.g.,

Fensome et al., 1996; Wiggan et al., 2017). An extensive body of literature indicates that among the spiniferate dinoflagellate cysts, *Cannosphaeropsis* was highly successful, with the genus spanning much of the Cretaceous to Neogene from ~130 Ma to ~2.8 Ma and several species constrained to narrow chronostratigraphic ranges presenting biostratigraphy utility (Fig. 3.5). Informal species left in open nomenclature referred to *Cannosphaeropsis* from older strata (e.g., Balduzzi et al., 1992) as well as from post-Neogene deposits (e.g., Costa and Downie, 1979) are attributable to other genera. The first species emerged during the Early Cretaceous. Known only from two reports, *C. hughesii* survived for ~4 myr from its first appearance datum (FAD) at ~131 Ma in the late Hauterivian to its last appearance datum (LAD) at ~127 Ma in the early Barremian (Harding, 1990; Heilmann-Clausen and Thomsen, 1995) followed by *C. australis*, with four records, which existed for ~12 myr from late Aptian (FAD ~119 Ma) to early Albian (LAD ~107 Ma) time (e.g., Riding and Helby, 2001; Backhouse, 2006). The type species, *C. utinensis*, may not have survived the longest, but it is the most commonly observed in deep time studies (Fig. 3.5). Unillustrated reports describe the species from rocks as old as Aptian (e.g., Allameh et al., 2011), however, its definitive FAD can be placed at ~97 Ma in the middle Cenomanian (Deaf et al., 2014) and its LAD at ~53 Ma in the Ypresian (e.g., King et al., 2018) beyond a reasonable doubt of reworking. Although *C. utinensis* is long-ranging, it is the eponymous taxon in a number of regional biostratigraphic zonation schemes for the Maastrichtian of the North Sea (Schiøler and Wilson, 1993), North Africa (Soliman and Slimani, 2019) and the Middle East (Eshet et al., 1994; Hoek et al., 1996).

Cannosphaeropsis utinensis, the motile dinoflagellate of which was presumably the root stock of all subsequent species, is the sole representative of the genus for most of the Late Cretaceous until the appearance of *C. franciscana* in the latest Maastrichtian (FAD ~66.3 Ma) which persists for some ~4.5–5 myr, at least until the earliest Selandian (LAD ~61.5 Ma) as shown in the present study (Fig. 3.5). *Cannosphaeropsis williamsii*, *C. quattrocchiai* and *C. passio* all develop in the Paleogene. The species with greatest *Nematosphaeropsis* affinity (Sarjeant, 1986), *C. williamsii*, spans ~36 myr from the Danian (FAD ~64 Ma) into the Rupelian (e.g., Williams and Brideaux, 1975; Châteauneuf, 1980, both as *Adnatosphaeridium reticulense*). Records attributable to *C. quattrocchiai* indicate its presence over an expanse of at least 31 myr (Fig. 3.5). There exists one unillustrated report from strata presumed to be in proximity to the K/Pg boundary (Gammero and Archangelsky, 1981, as *Cannosphaeropsis* aff. *utinensis*).

However, following its emergence in the late Eocene (Guerstein, 1990), the species would endure until the onset of the Pliocene cooling phase (e.g., Ravelo et al., 2004) with a LAD at ~2.8 Ma (Besems, 1993, as *C. cf. utinensis*). *Cannosphaeropsis passio* likely ranges for a period of ~25 myr (Fig. 3.5). One questionable unillustrated report places its range base in the early Danian (Beiranvand et al., 2014), but the unequivocal FAD for the species lies in the early Rupelian at ~31.5 Ma (Schiøler, 2005) with a Messinian LAD at ~6.5 Ma (Brown and Downie, 1985). In studies of Neogene assemblages, *C. passio* is most notably used as zonal marker for the middle to late Serravallian (e.g., de Verteuil and Norris, 1996; Strauss et al., 2001) preceding the period of late middle Miocene sea level fall (Strauss et al., 2001).

3.7.5 Paleobiogeography

A range of dinoflagellate cyst taxa are subject to latitudinal and oceanographic constraints corresponding to global climate zones and precise marine conditions as evidenced by work on modern species (e.g., Dale, 1996; Mudie and Harland, 1996; Zonneveld et al., 2013; de Vernal et al., 2020). Similar consistencies have also been observed in the fossil record (e.g., Lentin and Williams, 1980; Brinkhuis et al., 1998) and *Cannosphaeropsis* appears to be among those taxa which exhibited sensitivity to global temperature gradients (Fig. 3.7). *Cannosphaeropsis utinensis* is the only demonstrably cosmopolitan species despite Pearce et al. (2020, fig. 17f) having retained the Cenozoic South American records previously reassigned to *Cannosphaeropsis quattrocchiaie* by Guerstein et al. (2001) as well as having synonymized records of *Cannosphaeropsis australis* from the Lower Cretaceous of Australia. Based on the lower Maastrichtian record from ODP Site 748C on the Kerguelen Plateau in the southern Indian Ocean (Mao and Mohr, 1992) which has undergone little displacement since its formation (Inokuchi and Heider, 1992) and the upper Maastrichtian record from the Norwegian Sea (Radmacher et al., 2015) which has migrated considerably (e.g., Cao et al., 2017), the paleolatitudinal range of *C. utinensis* can be placed at ~60 °N to ~58 °S indicating a preference for middle to low latitude warm boreal to tropical waters.

While *C. utinensis* attained a worldwide distribution, all other members of the genus show at least some degree of regional endemism (Fig. 3.7). Illustrated reports of *Cannosphaeropsis*

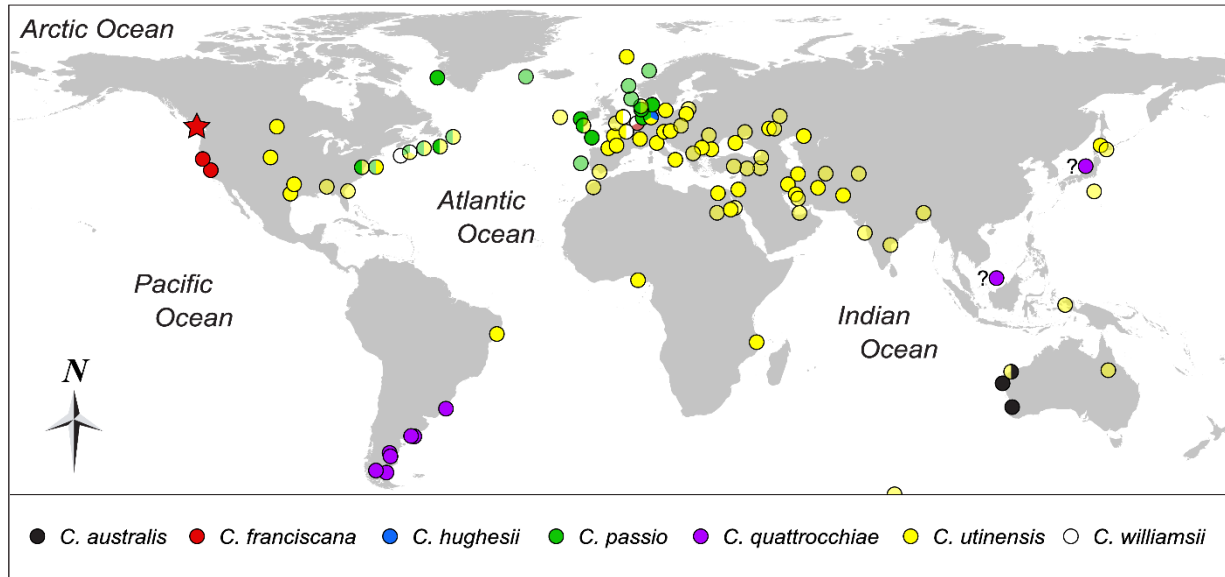


Figure 3.7. Geographic distribution of the seven accepted species belonging to the genus *Cannosphaeropsis* following Fensome et al. (2019), based on reports in the published literature. Point color opacity denotes unillustrated cyst records whereas solid points denote illustrated records. Question marks denote uncertainty herein pertaining to species assignment. Star = location of the present study area.

franciscana beyond this study are limited to the northeastern Pacific (California: Drugg, 1967; Damassa, 1979; British Columbia: McLachlan and Pospelova, 2021) with only one other written account from Europe (Belgium: Slimani et al., 2011). Likewise, *Cannosphaeropsis passio* is restricted to the North Atlantic and North Sea region (e.g., de Verteuil and Norris, 1996; Schiøler, 2005; Fensome et al., 2016) and *Cannosphaeropsis hughesii* is exclusive to northern Germany (Harding, 1990; Heilmann-Clausen and Thomsen, 1995). Similarly, *Cannosphaeropsis williamsii* hails from the North Atlantic and northern Europe (e.g., offshore eastern Canada: Williams and Brideaux, 1975; Belgium: Schumacker-Lambry, 1978; France: Châteauneuf, 1980, all as *Adnatosphaeridium reticulense*). Apart from two possible occurrences in the western Pacific (Japan: Harada and Matsuoka, 1974, as *Cannosphaeropsis* sp.; offshore Borneo: Besems, 1993, as *C. cf. utinensis*), *C. quattrocchiai* is known only from the Southern Hemisphere along the Atlantic margin of South America (e.g., Argentina: Gamero and Archangelsky, 1981, as *C. aff. utinensis*; Guerstein et al., 2001; Brasil: Premaor et al., 2018). Records of *C. australis* are confined to Western Australia where the species approached ~60 °S during the Aptian, in light of

current mapping projections (e.g., Cao et al., 2017). Aside from preservation and investigation biases, the paleogeographic distribution of *Cannosphaeropsis* species seems to indicate regional specialization which may offer further insight into the subjectivity of this group to paleoenvironmental controls and some utility toward reconstructions of paleoclimate, paleocurrent circulation patterns and ocean basin evolution.

3.8 Conclusions

Spiniferate gonyaulacaceans exhibit some of the greatest plasticity among dinoflagellate cysts attributable to both living species and those in the fossil record. Exceptionally preserved specimens of *Cannosphaeropsis franciscana* recovered from the Oyster Bay Formation succession exposed on eastern Vancouver Island, British Columbia, have presented the opportunity to elucidate the array of taxonomically significant elements which can manifest within a species. Extensive SEM analysis of a suite of *C. franciscana* cysts has enabled the observation of an unprecedented range of morphological variation within a single species belonging to the *Spiniferites* group necessitating taxonomic revisions to the species and the genus *Cannosphaeropsis*. The palynological context of *C. franciscana*, through assemblage association, calculations of cyst concentrations and their relative abundance, also indicates that these forms are reflective of an open marine paleoecological preference. Aside from discernible trends in body shape and process development, biostratigraphy reveals the geologically sudden onset and decline of dense vesiculation characterizing ephemeral subspecies in the earliest Danian. Therefore, the vesiculate wall structure of *C. f.* subsp. *vacuoseptata* subsp. nov. and *C. f.* subsp. *vesiculata* subsp. nov. may represent a localized ecophenotypic response to suboptimal paleoenvironmental conditions in an unstable offshore setting during the transgressive phase after the terminal Cretaceous event. Assemblage data from the studied interval also indicates that *Hafniasphaera* spp. increase in nutrient-rich coastal waters during the Danian when *Spiniferites* spp. are abundant and primary productivity becomes heightened. This observation suggests a relationship between the two genera with vesiculation manifesting as a possible means to maintain cyst buoyancy and slow descent under more stratified conditions in the water column with more nutrient input following the Maastrichtian. More broadly, a review of over 350 peer-reviewed published reports pertaining to all formally recognized members of *Cannosphaeropsis*

and *Hafniasphaera* sees these taxa as having been specialized constituents of the marine phytoplankton community that through further research could provide avenues toward refined paleoenvironmental reconstructions and a greater understanding of past climate fluctuations.

3.9 Acknowledgments

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Chapter 4

Phelodinium fensomei sp. nov.: a protoperidineacean dinoflagellate cyst from the lower Paleocene (Danian) of the Oyster Bay Formation, Vancouver Island, Canada¹

4.1 Abstract

Phelodinium fensomei is a new species of organic-walled dinoflagellate cyst described from the Appian Way section of the of the Oyster Bay Formation, Vancouver Island, British Columbia, Canada. *Phelodinium fensomei* sp. nov. is distinct from other species of *Phelodinium* in its unique combination of characters which include an elongate epicyst, bilobate endocyst antapex, and microgranulate to verrucate surface ornamentation. The species occurs exclusively within Dinoflagellate Cyst Zone D4 of the Oyster Bay Formation along with the Danian indicator taxon *Danea californica*. This is also the first study to perform scanning electron microscopy and epifluorescence analysis on a specimen belonging to the protoperidinioid genus *Phelodinium*, revealing minute features and a negative response to ultraviolet light exposure indicating a heterotrophic feeding strategy for the motile cell. Although *P. fensomei* sp. nov. occurs at markedly low relative and absolute abundances in the examined interval, it is restricted to strata of Danian age suggesting potential biostratigraphic utility.

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4.2 Introduction

Sedimentary rocks of early Paleogene age are sparsely distributed along the west coast of British Columbia and Washington State with isolated beds scattered throughout the region, unconformably overlying the Upper Cretaceous strata of the Nanaimo Group (e.g., Mustard and Rouse, 1992; Mustoe et al., 2007; Mathewes et al., 2020). The Oyster Bay Formation is a ~93.5 m-thick succession consisting of mudstone to conglomerate intervals as established from a composite of three sections within a ≥ 6.5 km lateral extent (Fig. 4.1). The formation is the only unit with lower Paleocene beds exposed along eastern Vancouver Island with the age determined through relative dating during a comprehensive survey of its marine palynological assemblages. Using a dinoflagellate cyst-based approach, it was established that the Oyster Bay Formation spans the upper Maastrichtian–lower Selandian (McLachlan and Pospelova, 2021). Specimens of the dinoflagellate cyst *Phelodinium fensomei* sp. nov. were present among the taxa examined from the samples obtained from the Appian Way section in the aforementioned study which contained the fibrous cribroperidnioid species *Danea californica*, a global marker for strata of Danian age (e.g., Hansen, 1977; Moshkovitz and Habib, 1993; Williams et al., 2004). The species was found to occur infrequently, being among the rarest dinoflagellate cysts recovered.

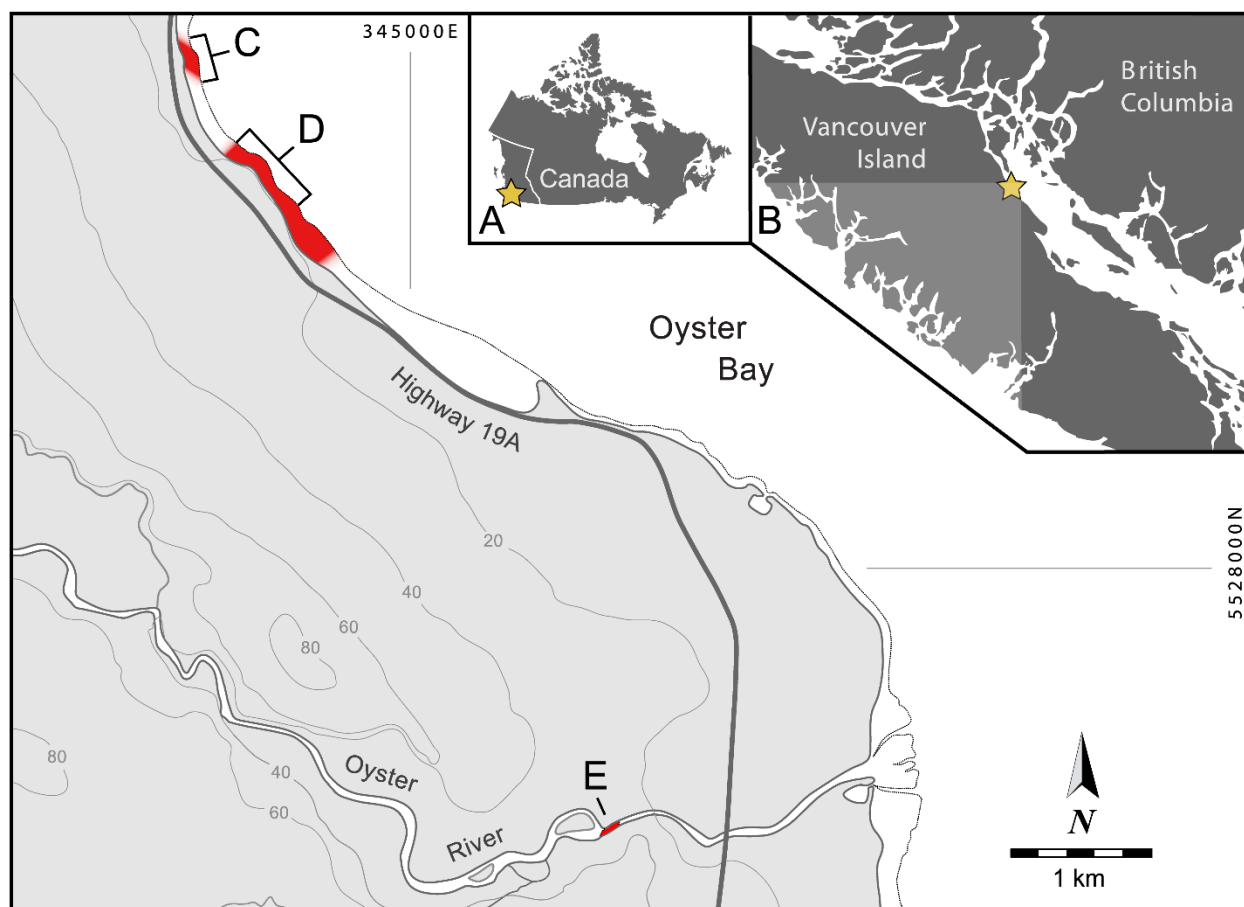


Figure 4.1. **A**, Location of Vancouver Island (star), British Columbia, Canada; **B**, Location of the study area (star) and Oyster Bay Formation localities, east coast Vancouver Island; **C**, Lynnwood coastal section; **D**, Appian Way coastal section; **E**, Oyster River section. Red areas denote outcrop.

4.3 Materials and methods

Ninety sedimentary rock samples from throughout the Oyster Bay Formation succession were processed for palynological analysis. Eighty-seven were collected in-situ, while three samples were taken from float concretionary mudstone matrices collected at the Appian Way locality during the initial investigation. The stratigraphic position of each sample is plotted for the Appian Way section in Fig. 4.2. Samples were prepared using a standardized dinoflagellate cyst extraction procedure (e.g., Pospelova et al., 2010). For each of the samples, $\sim 2 \text{ cm}^3$ of matrix were placed in 50 ml polypropylene test tubes with an average dry weight of $\sim 5.4 \text{ g}$. Samples were treated repeatedly with 10 ml of 10% room-temperature hydrochloric acid (HCl) to dissolve

any carbonate content. A single *Lycopodium clavatum* tablet of batch #177745 (produced at the Department of Geology, University of Lund, Lund, Sweden) or batch #2013001 (produced at the Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences, Nanjing, China) was added to each sample for the purpose of dinoflagellate cyst absolute abundances calculation (e.g., Benninghoff, 1962; Stockmarr, 1971; Mertens et al., 2012c).

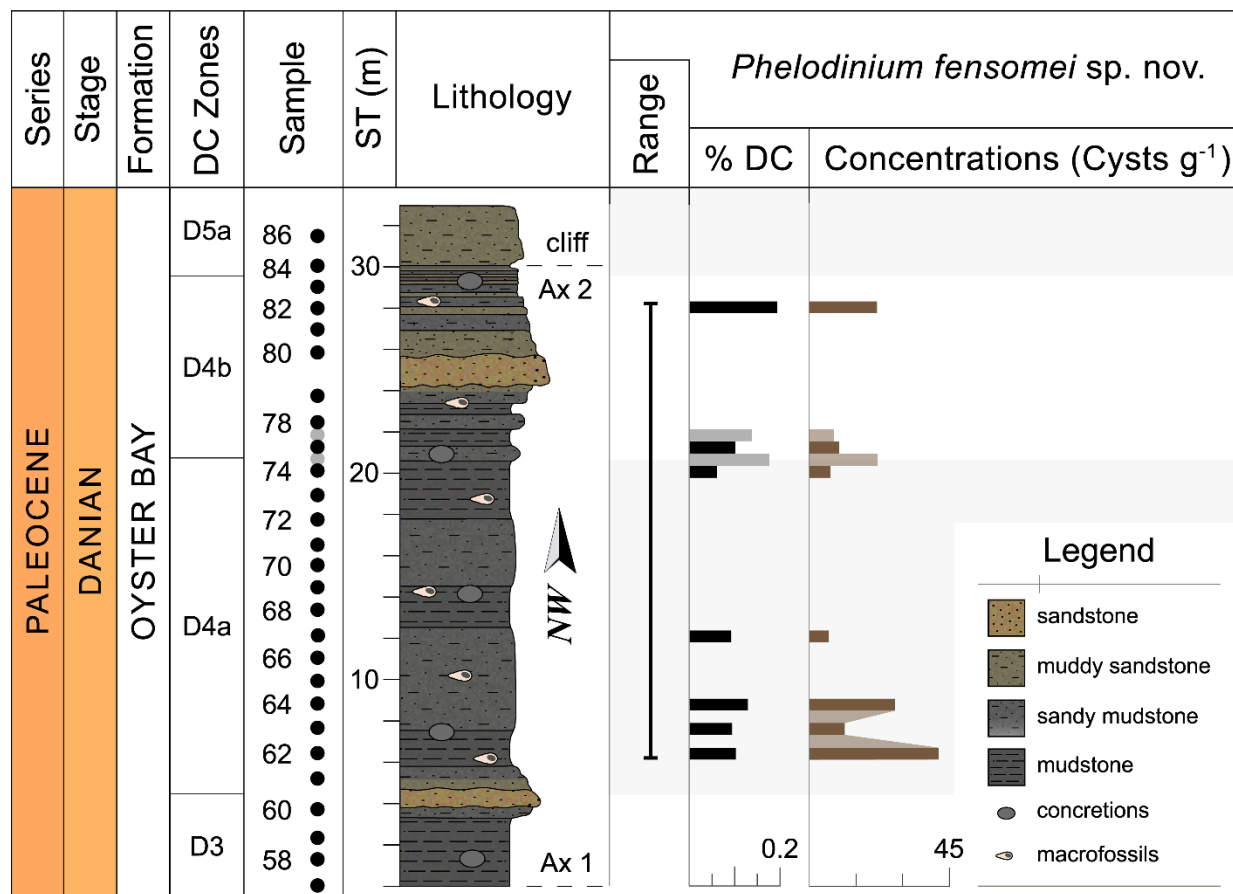


Figure 4.2. Schematic framework of the measured Appian Way section of the Oyster Bay Formation with plotted stratigraphic range, relative abundances, and cyst concentrations of *Phelodinium fensomei* sp. nov. Dinoflagellate cyst (DC) zones of McLachlan and Pospelova (in press). Grey points denote samples obtained from float matrices. ST = stratigraphic level above base of section. Ax 1 = anticline axis. Ax 2 = syncline axis.

Following HCl, each sample was treated with 20 ml of 48% room-temperature hydrofluoric acid (HF) from ten to twenty-five days depending on the amount of silicate minerals to be broken

down. After the matrix dissolution stage, each sample underwent one round of HCl and two rinses of reverse osmosis water to remove any HF residue before final sieving through 120 μm and 15 μm Nitex nylon mesh to remove remaining particles. The samples underwent up to one minute of ultrasonic agitation to dislodge minute sediment particles from the dinoflagellate cysts (Mertens et al., 2012c; Price et al., 2016) and centrifuging took place at 3600 rpm. Following the sieving stage, residue was mounted in glycerin jelly on microscope slides for bright-field microscopy. One *Phelodinium fensomei* sp. nov. specimen was isolated and transferred to an aluminum stub with a micropipette in preparation for scanning electron microscopy (SEM). The stub was then coated with a gold/palladium mix using an Anatech Hummer VI sputter coater for a total thickness of 20 nm. All microfossil samples are assigned catalogue numbers and housed within the Paleoenvironmental / Marine Palynology Laboratory, School of Earth and Ocean Sciences, University of Victoria (Victoria, British Columbia, Canada).

Identification and counts of dinoflagellate cysts with more than half of their structure intact were conducted at 600x magnification. Counts exceeding 400 dinoflagellate cysts were reached where possible (e.g., Slimani et al., 2016; Chakir et al., 2020) over a maximum of four slides to obtain optimal relative abundance distributions given the high-diversity assemblages. Where present, specimens of *P. fensomei* sp. nov. were counted relative to at least 1% of the introduced *Lycopodium clavatum* spores from each tablet as to place as a control on their sample size for absolute abundance calculation. A series of eight measurements were taken from selected specimens where possible in accordance with structural integrity and orientation (Fig. 4.3).

Epifluorescence has been used as an indicator of original chlorophyll presence in dinoflagellates (e.g., Wood, 1955; Lessard and Swift, 1986; Brenner and Biebow, 2001; Pospelova and Head, 2002). Therefore, epifluorescence analysis of specimens was performed using a Nikon Intensilight C-HGFI precentered fiber illuminator by exposing them to ultraviolet light for a minimum of two minutes. Bright-field photomicrographs were taken under 600x magnification with a Nikon DS-5M-L1 digital camera system mounted on a Nikon Eclipse 80i light microscope. For clarity of image presentation, extraneous particulate debris were removed from the field of view (Riding and Head, 2018) with a brush tool using Macromedia Fireworks 8 software if the material was not in contact with the specimen ambitus. SEM micrographs were taken using a Hitachi S-4800 SEM at the Advanced Microscopy Facility (University of Victoria, Victoria, Canada) and composite images were prepared in Macromedia Fireworks 8.

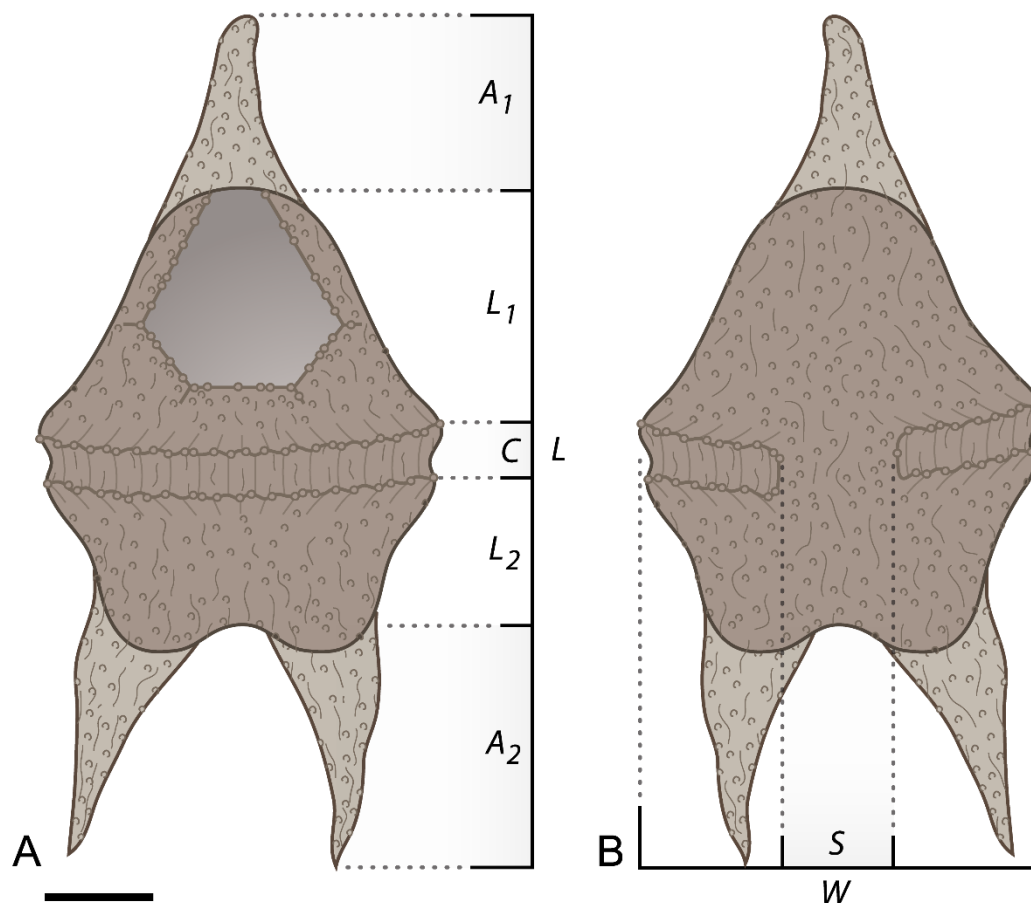


Figure 4.3. Diagram illustrating measurement scheme applied to specimens of *Phelodinium fensomei* sp. nov. A, dorsal view; L = total length; A_1 = apical horn length; L_1 = epicyst length, taken along axis; C = cingulum width; L_2 = hypocyst length, taken along axis; A_2 = longest antapical horn length. B, ventral view; W = endophragm width, taken mid-cingulum; S = sulcal width. Scale bar = 10 μm for average size reference.

4.4 Results

4.4.1 Marine palynology

The marine palynological assemblages of the Oyster Bay Formation are very diverse with the entire succession yielding over 100 dinoflagellate cysts species across six families from those samples which were productive. All cysts of *Phelodinium fensomei* sp. nov. are generally very well preserved and were recovered from only nine of the 90 samples surveyed in the original

palynological study of the formation (McLachlan and Pospelova, 2021), two of which were obtained from float concretionary mudstone matrices. The stratigraphic range of the species along with cyst relative and absolute abundances are plotted against the dinoflagellate cyst zones defined by McLachlan and Pospelova (2021) with the provenance of float samples having been inferred through lithological and palynological assemblage correlation (Fig. 4.2). Specimen counts and absolute abundance data are presented in Appendix 3, Table 1.

Phelodinium fensomei sp. nov. is restricted to an interval from 6.6–28.0 m within the Appian Way section corresponding to Zone D4 of the Oyster Bay Formation. The species is also exceedingly rare. In productive samples, its cyst concentrations range from 7–44 cysts g⁻¹ (avg. 18 cysts g⁻¹) with its highest absolute abundance being found in Sample 62 at its stratigraphic range base. When present, its relative abundances have a range of merely 0.06–0.19% (avg. 0.13%) of the dinoflagellate cyst assemblages with its highest proportions occurring in Sample 82 at its stratigraphic range top (Fig. 4.2). Specimens of *P. fensomei* sp. nov. possess a wall composition which is unresponsive to epifluorescent microscopy in yielding no illumination; a negative test result for primary production capability (Appendix 3, Supplementary Fig. 1).

4.4.2 Systematic paleontology

The approach to classification and nomenclature follows that of Williams et al. (2017) and Fensome et al. (2019). The conventional Kofoed Tabulation System (Kofoed, 1907a, 1907b, 1909, 1911) is employed in plate identification. Other descriptive morphological terminology follows that of Fensome and Williams (2005). Measurements obtained from specimens analyzed through both transmitted light and scanning electron microscopy are listed in Appendix 3, Table 2, along with England Finder (EF) coordinates which are provided for all type and reference specimens. The coordinates are taken with the slide label to the right.

Division: DINOFLAGELLATA (Bütschli, 1885) Fensome et al., 1993

Subdivision: DINOKARYOTA Fensome et al., 1993

Class: DINOPHYCEAE Pascher, 1914

Subclass: PERIDINIPHYCIDAE Fensome et al., 1993

Order: PERIDINIALES Haeckel, 1894

Suborder: PERIDINIINEAE (autonym)

Family: PROTOPERIDINIACEAE Bujak and Davies in Fensome et al., 1998

Subfamily: PROTOPERIDINIOIDEAE (autonym)

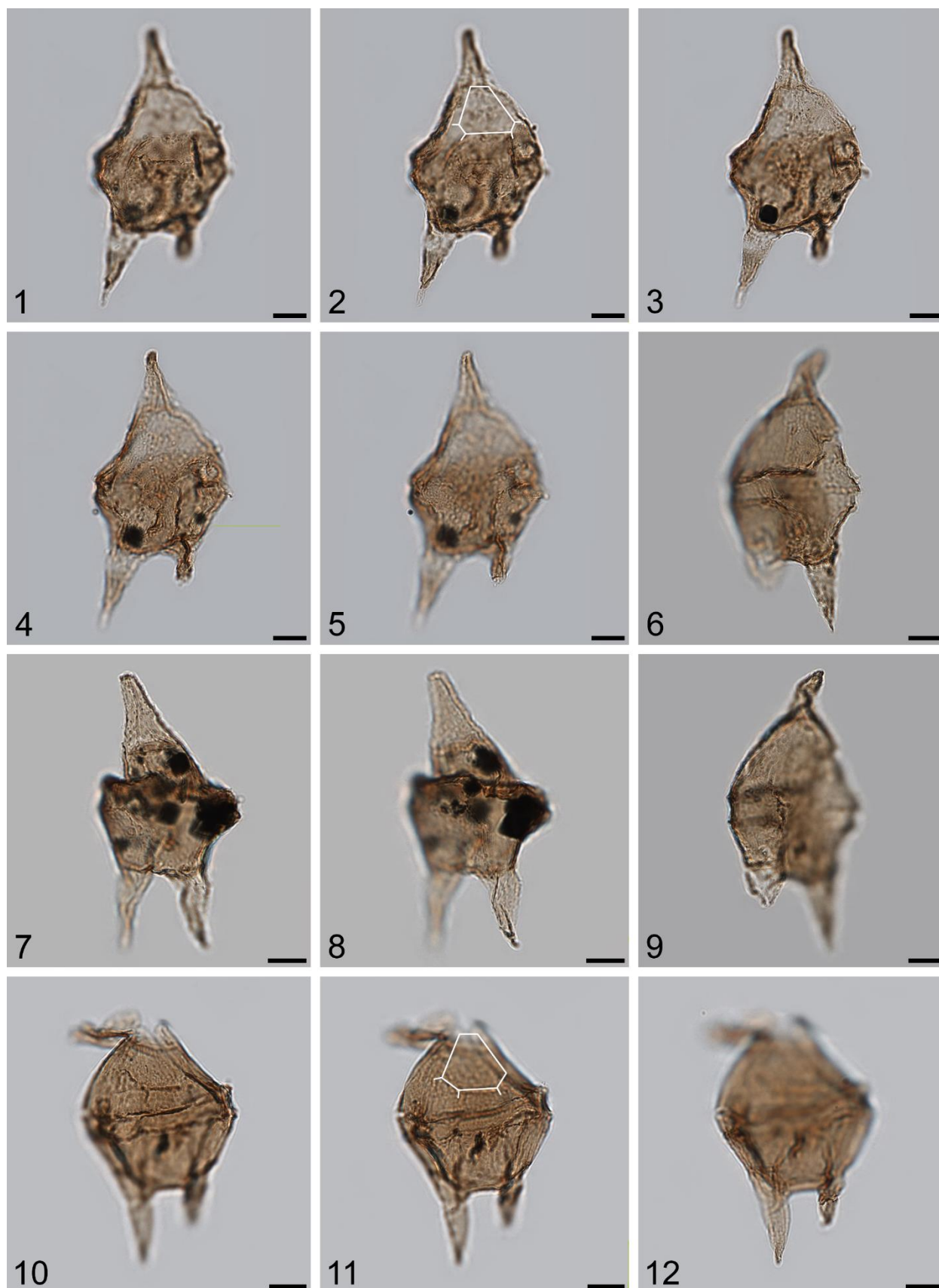
Genus: **PHELODINIUM** (Stover and Evitt, 1978) Mao and Norris, 1988

Type species: *Deflandrea pentagonalis* Corradini, 1973.

Synopsis: A dorso-ventrally compressed, proximate protoperidiniacean (protoperidinioidean) cyst with one apical and two antapical horns. The cyst is pentagonal with convex to concave lateral sides. Apical and antapical horns can be of variable length, are usually distally acuminate, and may have solid tips. Cornucavate where two wall layers can be discerned. Cingulum sometimes present. Endocyst, where observable, and pericyst smooth or ornamented with features of low relief ranging from faint microfolds to echinae. Archeopyle intercalary, with formula I_{2a}, the second anterior intercalary plate is deltaform; operculum usually free.

Remarks: The synopsis provided for the genus is essentially that of Fensome et al. (2016) expanding on the original diagnosis of Stover and Evitt (1978) and subsequent emendation of Mao and Norris (1988).

Comparison: A member of the Protoperidiniaceae, *Phelodinium* differs in its absence of intracingular plate boundaries from other taxa with superficially similar morphology belonging to the Peridiniaceae (Fensome et al., 1993) such as *Cerodinium* (Vozzhennikova, 1963) Lentin and Williams, 1987, *Deflandrea* (Eisenack, 1938) Lentin and Williams, 1976, and *Lejeunecysta* (Artzner and Dörhöfer, 1978) Bujak in Bujak et al., 1980. The secondary taxonomic character that distinguishes *Phelodinium* from the deflandreoid genera *Cerodinium* and *Deflandrea* is the absence of an epipericoel such that the periphragm and periarcheopyle are separated from the epicyst endophragm in a circumcavate to bicavate cyst. Additionally, the archeopyle geometry of *Phelodinium* differs from that of *Cerodinium* in the latter genus possessing an iso-deltaform to iso-thetaform hexa periarcheopyle and *Deflandrea* differs in possessing a lati-deltaform hexa periarcheopyle (e.g., Bujak and Davies, 1983; Lentin and Vozzhennikova, 1990; Fensome et al., 2009; Pearce et al., 2019). *Phelodinium* also differs from *Lejeunecysta* in being cornucavate whereas *Lejeunecysta* is acavate and autophragmal with rare exception in some specimens of *Lejeunecysta marieae* (Harland in Harland et al., 1991) Lentin and Williams, 1993 (Head, 1993).



← **Plate 4.1.** Bright-field photomicrographs of *Phelodinium fensomei* sp. nov. specimens recovered from the Appian Way section of the Oyster Bay Formation. 1–5, holotype RBCM P1566, Sample 62 (UVic 18-178, slide F, EF Q44/1), 6.6 m; 1, dorsal view, archeopyle in focus; 2, dorsal view, one-quarter focus, superimposed white lines denote archeopyle perimeter and adjoining plate contacts; 3, mid focus; 4, ventral view, three-quarters focus; 5, ventral view, sulcal margin in focus. 6, 9, paratype, Sample 62, 6.6 m (UVic 18-178, slide A, EF C41/3); 6, right lateral view, antapical horn in focus; 9, left lateral view, antapical horn in focus. 7, 8, paratype, Sample 62, 6.6 m (UVic 18-178, slide A, EF C39/3), note semi-collapsed epicyst and internal pyrite crystals; 7, apical horn scabrate to verrucate surface in focus; 8, right antapical horn scabrate to verrucate surface in focus. 10–12, paratype, Sample 62, 6.6 m (UVic 19-31, slide B, EF C35/0); 10, dorsal view of archeopyle margin with operculum in place; 11, dorsal view, one-quarter focus, superimposed white lines denote archeopyle perimeter and adjoining plate contacts; 12, ventral view with left antapical horn terminus in focus. Scale bars = 10 μm .

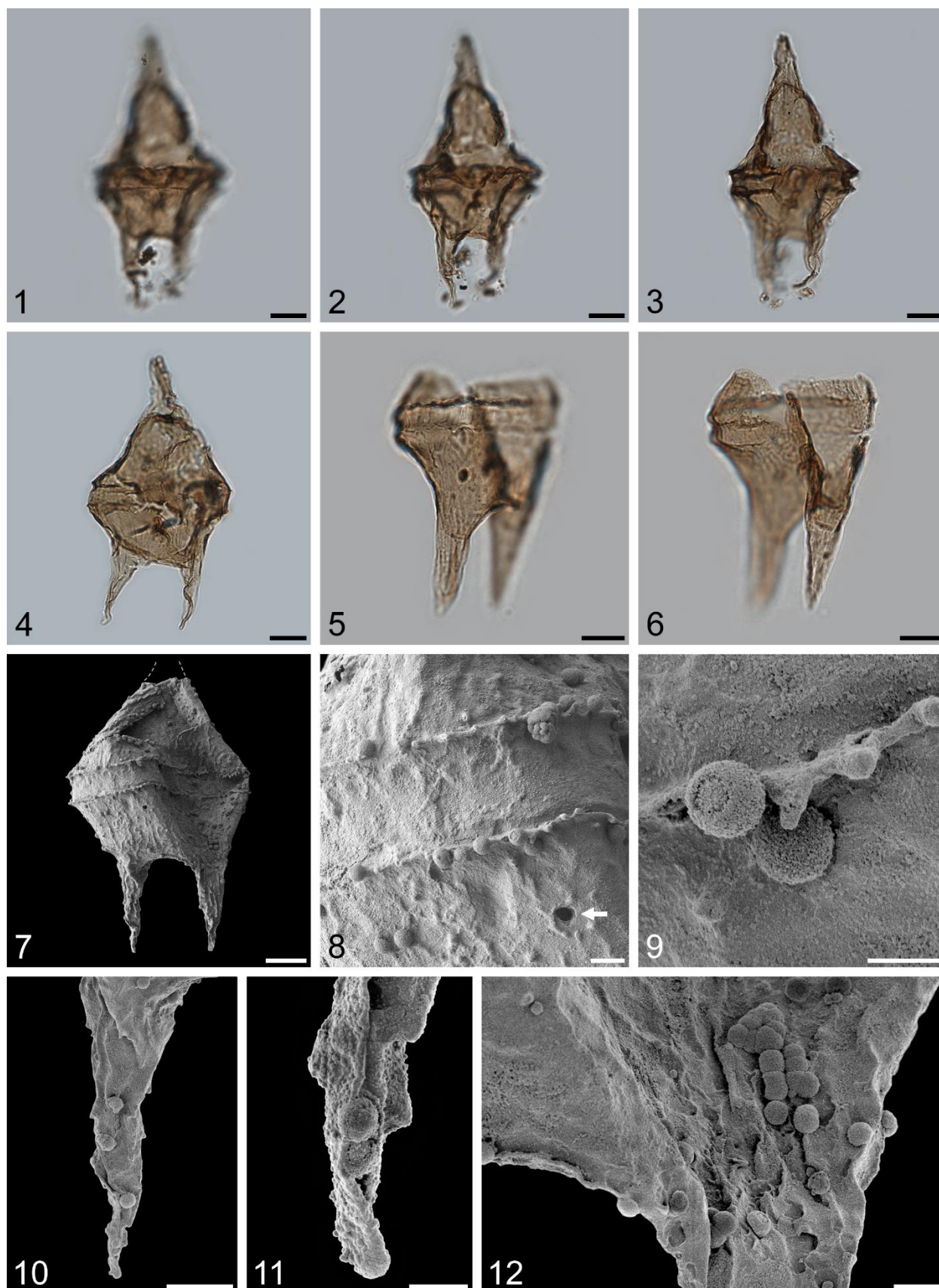
***Phelodinium fensomei* sp. nov.**

Plate 4.1, figs. 1–12; Plate 4.2, figs. 1–12; Fig. 4.3A, B; Fig. 4.4; Fig. 4.5.

Etymology: Named in honor of Dr. Robert A. Fensome of the Geological Survey of Canada (Atlantic), Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada, for his prolific contributions to the taxonomy and systematics of fossil dinoflagellate cysts.

Holotype: The holotype (Plate 4.1, figs. 1–5) is specimen RBCM P1566 collected from Sample 62 (UVic 18-178, slide F, EF Q44/1) along the intertidal outcrop of the Appian Way section (UTM Grid Reference 343770E, 5531007N, Zone 10U; WGS84) and Dinoflagellate Cyst Zone D4 (Danian) of the Oyster Bay Formation, Vancouver Island, British Columbia. It is housed within the paleontological collections of the Royal British Columbia Museum, Victoria, British Columbia, Canada. Total length: 84.5 μm , total width: 38.9 μm , epicyst length: 23.7 μm , hypocyst length: 15.1 μm , cingulum width: 6.1 μm , apical horn length: 16.6 μm , longest antapical horn length: 24.1 μm , sulcal width: 11.8 μm .

Paratypes: All from the exposures of the Appian Way section of the Oyster Bay Formation, Vancouver Island, British Columbia. Plate 4.1, figs. 6, 9, Sample 62, 6.6 m; total length (L): 85.5 μm , total width (W): 35.7 μm , epicyst length (L_1): 23.5 μm , hypocyst length (L_2): 18.6 μm , cingulum width (C): 6.1 μm , apical horn length (A_1): 16.1 μm , longest antapical horn length (A_2): 21.1 μm , sulcal width (S): 12.8 μm . Plate 4.1, figs. 7, 8, Sample 62, 6.6 m; W : 35.3 μm , L_1 : 23.1



← **Plate 4.2.** Bright-field photomicrographs and scanning electron micrographs (SEM) of *Phelodinium fensomei* sp. nov. specimens recovered from the Appian Way section of the Oyster Bay Formation. 1–3, paratype, Sample 75, ~20–22 m (UVic 17-689, slide E, EF C39/0), scale bar = 10 μm ; 1, dorsal view, cingulum in focus; 2, dorsal view, partially detached operculum in focus; 3, ventral view, sulcal margin in focus. 4, paratype, Sample 75, ~20–22 m (UVic 17-689, slide C, EF U47/1), antapical horns in focus, scale bar = 10 μm . 5, 6, paratype, Sample 62, 6.6 m (UVic 18-178, slide A, C43/3), scale bar = 10 μm ; 5, left antapical horn in focus, note fine nodate to verrucate ornament in alignment along periphragm microfolds; 6, right antapical horn in focus, note dense scabrate to verrucate surface ornament. 7–12, paratype, Sample 62, 6.6 m (UVic 19-31, SEM Stub P); 7, dorsal view, superimposed white dashed lines denote apical horn base in its absence due to post depositional damage, scale bar = 10 μm ; 8, enlarged view of mid-dorsal cingular region with epicyst and cingular plate series contact demarcated by raised nodae and verrucae, arrow denotes perforate foveolation, scale bar = 2 μm ; 9, enlarged view of nodae and verrucae arising from ridge along point of contact between epicyst and cingular plate series, scale bar = 1 μm ; 10, enlarged view of left antapical horn, scale bar = 5 μm ; 11, enlarged view of left antapical horn terminus and surface ornamentation, note dense concentration of scabrae and verrucae, scale bar = 1 μm ; 12, enlarged view of hypocyst surface ornament above right antapical horn, note microfolds, verrucae, and foveolae, scale bar = 2 μm .

μm , A_1 : 18.2 μm , A_2 : 18 μm . Plate 4.1, figs. 10–12, Sample 62, 6.6 m; L : 83.4 μm , W : 40.5 μm , L_1 : 23.6 μm , L_2 : 16.1 μm , C : 4.9 μm , A_1 : 17.6 μm , A_2 : 21.1 μm , S : 9.5 μm . Plate 4.2, figs. 1–3, Sample 75, ~20–22 m; L : 73.5 μm , W : 33.4 μm , L_1 : 25.8 μm , L_2 : 11.5 μm , C : 4.9 μm , A_1 : 12.6 μm , A_2 : 18.6 μm , S : 12.2 μm . Plate 4.2, figs. 4, Sample 75, ~20–22 m; L : 73.5 μm , W : 37.9 μm , L_1 : 20.5 μm , L_2 : 14.4 μm , C : 4.7 μm , A_1 : 16.4 μm , A_2 : 17.4 μm , S : 11.4 μm . Plate 4.2, figs. 5, 6, Sample 62, 6.6 m; L_2 : 19.1 μm , C : 4.7 μm , A_2 : 20.3 μm . Plate 4.2, figs. 7–12, Sample 62, 6.6 m; W : 42.9 μm , L_1 : 20 μm , L_2 : 17.4 μm , C : 6.2 μm , A_2 : 23.2 μm .

Type locality: Appian Way coastal section of the Oyster Bay Formation, eastern Vancouver Island, British Columbia. Horizontal extent from northeast to southwest: UTM Grid Reference 343520E, 5531175N, Zone 10U (WGS84) to UTM Grid Reference 344200E, 55303807N, Zone 10U (WGS84).

Diagnosis: A species of *Phelodinium* with an epicyst longer than the hypocyst and a microgranulate periphragm marked by sparsely and unevenly distributed scabrae and verrucae. Endophragm antapically bilobate with protrusion into the antapical horns.

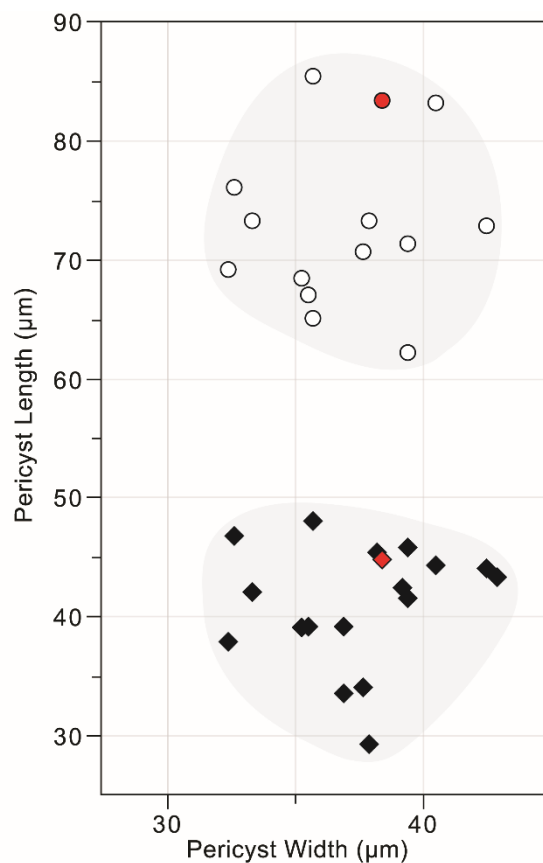


Figure 4.4. Measurements of *Phelodinium fensomei* sp. nov. Black diamonds = endocyst dimensions. White circles = pericyst dimensions. Red diamonds and circles represent the dimensions of the holotype endocyst and pericyst, respectively.

Description: The endocyst ambitus is subpentagonal. Pericyst bearing one apical horn and two antapical horns; cornucavate with periphragm appressed to endocyst. Within the endocyst, the epicyst is typically longer than the hypocyst, both being separated by a clearly defined cingulum marked by fine transverse ridges. The antapical region is bilobate with protrusion of the endophragm into the antapical horns ranging from weak (e.g., holotype, Plate 4.1, figs. 1–5) to pronounced (paratype, Plate 4.2, figs. 5, 6). The apical and antapical horns taper gradually with the apical horn terminus being blunt and the antapical horn termini being acuminate. The left antapical horn may be longer than the right antapical horn, but both are generally of approximately equal length. Periphragm ornamentation consists of a densely microgranulate surface texture (granules $< 0.3 \mu\text{m}$ in diameter) and sparse scabrae with verrucae unevenly

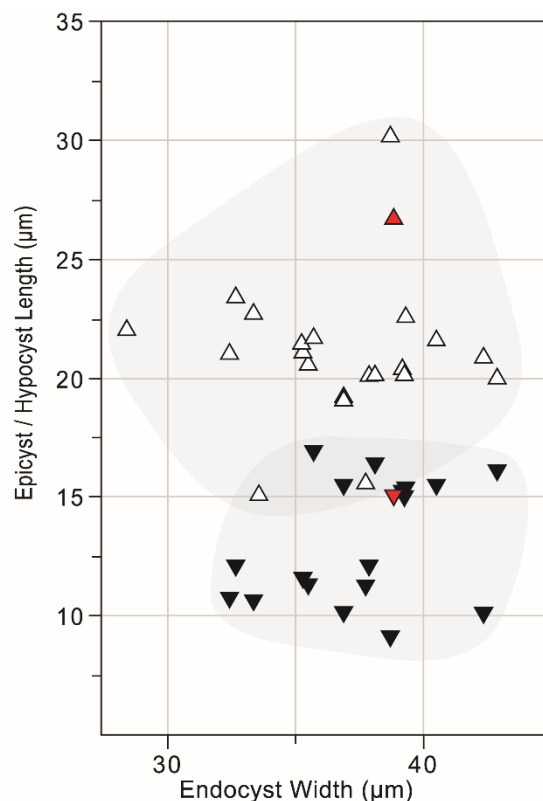


Figure 4.5. Measurements of *Phelodinium fensomei* sp. nov. White upward-directed triangles = epicyst dimensions. Black downward-directed triangles = hypocyst dimensions. Red upward-directed and downward-directed triangles represent the dimensions of the holotype epicyst and hypocyst, respectively.

distributed across the entire cyst. Nodae and verrucae are occasionally aligned along the cingular ridges (Plate 4.2, fig. 9) and low-relief, longitudinal microfolds accentuate an overall faintly wrinkled, striate appearance (Plate 4.2, figs. 5–7). Scabrae are more densely concentrated along the horn extremities as can be more readily seen through SEM (Plate 4.2, fig. 11). Verrucae are typically between 0.3–1 μm in diameter (Plate 4.2, fig. 9, 12). More uncommonly, foveolations may occur either in patches (Plate 4.2, fig. 12) or in isolation (Plate 2, fig. 8). The archeopyle is formed by isodeltaform hexa intercalary plate 2a and the operculum may be either fully detached (Plate 4.1, figs. 1, 2) or fully attached (Plate 4.1, figs. 10, 11); formula I_{2a} . The cyst exhibits a light brown pigmentation.

Dimensions: Total length: 55.1 (73.1) 84.5 μm , number of specimens: 18; holotype: 84.5 μm (Fig. 4.4). Total width: 28.4 (36.9) 42.9, number of specimens: 22; holotype: 38.9 μm (Fig. 4.4). Epicyst length: 14.2 (21.7) 30.8 μm , number of specimens: 26; holotype: 23.7 μm (Fig. 4.5).

Hypocyst length: 8.3 (14.3) 19.2 μm , number of specimens: 25; holotype: 15.1 μm (Fig. 4.5). Cingulum width: 2.8 (4.9) 6.3 μm , number of specimens: 28; holotype: 6.1 μm . Apical horn length: 7.2 (15.3) 19.7 μm , number of specimens: 20; holotype: 16.6 μm . Longest antapical horn length: 8.5 (17.9) 24.1 μm , number of specimens: 24; holotype: 24.1 μm . Sulcal width: 8.7 (12) 15.2 μm , number of specimens: 20; holotype: 11.8 μm .

Stratigraphic range: *Phelodinium fensomei* is restricted to within Dinoflagellate Cyst Zone D4 (Danian) of the Oyster Bay Formation, Vancouver Island, British Columbia; 6.6–28.0 m in the Appian Way section (Fig. 4.2).

Comparison: As a member of the Protoperidiniaceae, *Phelodinium fensomei* sp. nov. differs from species within the Peridiniaceae in its absence of intracingular plate boundaries; a subtle but significant familial distinction. Additional morphological characters previously mentioned relating to cavation and archeopyle geometry also see differentiation from the closet peridineacean genera *Cerodinium* and *Deflandrea*. Similar to *Phelodinium*, many species of *Cerodinium* bear some form of longitudinal periphragm folds or striations often marked by aligned granulae (e.g., Drugg, 1967; Jain and Millepeid, 1973; Srivastava, 1995) and when present, projected ornament in the genus ranges from microgranulae to echinae (e.g., Lentin and Vozzhennikova, 1990; Nøhr-Hansen and Heilmann-Clausen, 2001). Alignment of granulae and echinae is also observed in several species of *Deflandrea*, although independent of longitudinal striations (e.g., Alberti, 1959; Cookson and Eisenack, 1965; Vozzhennikova, 1967).

Ornament approaching that of *P. fensomei* sp. nov. among the aforementioned deflandreoid genera is seen in the scabrae of *Deflandrea scabrata* Wilson, 1988 from the lower–middle Eocene of the Wanstead Formation, New Zealand. However, the scabrae of the species are restricted to a thick-walled, elipsoidal endophragm. *Deflandrea heterophlycta* Deflandre and Cookson, 1955 from the upper Eocene Browns Creek clays of southern Australia, bears irregularly dispersed tubercles which are more numerous and coarser towards the poles of a spherical endophragm. In terms of verrucae, *Cerodinium verrucosum* (Heisecke, 1970) Lentin and Williams, 1989 from the Danian Roca Formation of Argentina is the only species of *Cerodinium* with such ornamentation and possesses a subcircular to rhomboidal ambitus and minute, weakly developed horns. Scattered verrucae are also reported across the periphragm of *Deflandrea variabilis* Vieira et al., 2017, from the Danian of the Våle Formation offshore

Norway and the endophragm of *Deflandrea webbi* Wrenn and Hart, 1988, from the Eocene of the La Meseta Formation, Seymour Island, Antarctica. All four species are circumcavate.

Few protoperidinioid dinoflagellate cysts are comparable to *P. fensomei* sp. nov. with its distinct diminutive size, wall relationships, and microgranulate to verrucate ornamentation when observed at magnifications of at least 600x. Perhaps most similar is *Phelodinium?* *spinatum* He Chengquan, 1991 from the Paleocene strata of western China, but the species differs from *P. fensomei* sp. nov. in its ornamentation with rod-like echinae projected up to 2.5 μm in length. Also hailing from rocks of the same age and locality in China is *Phelodinium spinocapitatum* He Chengquan, 1991 with rod-like echinae of similar length to those of *P.?* *spinatum* but of ununiform distribution across the cyst. Among other species of *Phelodinium*, scabrae are only reported on the periphragm of *Phelodinium exilicornutum* Smith, 1992 from the upper Campanian–lower Maastrichtian of the López de Bertodano Formation on Vega Island, Antarctic Peninsula. *Phelodinium exilicornutum* is also distinguished *P. fensomei* sp. nov. by its larger dimensions and slender, tapering horns (Smith, 1992).

Phelodinium pachyceras Liengjarern et al., 1980 from the upper Eocene–lower Oligocene strata of the Isle of Wight bears well-developed horns with extensive cavation with minor endophragm antapical horn protrusion. The species differs from *P. fensomei* sp. nov. in having a granulate to echinate surface ornament along with a rounded triangular endophragm ambitus. Additionally, and most striking, Liengjarern et al. (1980, p. 486) describe the occasional presence of a pericoel between the antapical horns which is an atypical feature for the genus. The much larger *Phelodinium magnificum* (Stanley, 1965) Stover and Evitt, 1978 from the Paleocene Fort Union Formation of South Dakota, bears a smooth surface with small, irregularly positioned echinae.

Other species which approach the general morphology of *P. fensomei* sp. nov. exhibit lower relief features or lack ornamentation altogether. These include the type species *Phelodinium pentagonale* Corradini, 1973 from the Upper Cretaceous strata of northern Italy, with its smooth to granulate surface as well as the larger and wider, smooth-surfaced *Phelodinium harringtonii* Levy and Harwood, 2000 from the middle–upper Eocene erratics of Antarctica. Another species of closer resemblance is *Palaeoperidinium?* *tenue* Schumacker-Lambry, 1978 (a questionable assignment: Evitt et al., 1998) from the upper Paleocene strata of Belgium, which possesses

equivalent ambital shape, horn expression, archeopyle geometry, and size, but differs from *P. fensomei* sp. nov. in being only smooth to granulate and having an epi- and hypocyst of approximately equal length.

Protrusion of the endophragm with cornucavation is known in three similar species: *Phelodinium kozlowskii* (Górka, 1963) Lindgren, 1984 from the upper Maastrichtian strata of Poland, the aforementioned *P. magnificum*, and *Phelodinium tricuspe* (Wetzel, 1933) Lejeune-Carpentier and Sarjeant, 1981 presumably from the Upper Cretaceous flint erratics of northern Germany. These taxa are pentagonal with an angular endophragm which sharply protrudes into the apical and antapical horns. Harland (1973) and Harker and Sarjeant (1975) considered *P. kozlowskii* to be a taxonomic junior synonym of *P. tricuspe*, although Lindgren (1984) retained the species on the grounds that the former presents a lesser degree of concavity between the antapical horns as stated by Górka (1963). *Phelodinium kozlowskii* and *P. tricuspe* bear longitudinal striae with the latter species exhibiting fine surface granulation or punctation with more extreme lateral concavity of the epicyst and hypocyst. *Phelodinium longicorne* He Chengquan, 1991 from the Paleocene strata of western China is of similar size to *P. fensomei* sp. nov. with longitudinal folds, but the epicyst and hypocyst are of equal length, the horns are longer with a narrower taper, and while apparently microgranulate, its surface is free of scabrae and verrucae. The same character of longitudinal striae is described as irregular folds in *Phelodinium pentagonale* (Corradini, 1973) and wrinkles in *Phelodinium exilicornutum* (Smith, 1992).

4.5 Overview

Phelodinium fensomei sp. nov. is a rare and uniquely ornate protoperidiniacean dinoflagellate cyst that is constrained to the Danian-aged strata of the Oyster Bay Formation exposed at the Appian Way locality along the eastern coast of Vancouver Island, British Columbia. SEM micrographs reveal details of surface relief and texture which present a range of features including longitudinal microfolds, microgranules, nodae, scabrae, and verrucae. The scarcity of the species in relation to the abundance of other marine palynological taxa throughout the section indicates that *P. fensomei* sp. nov. was likely a specialized member of the phytoplankton

community in a high productivity setting. Like other protoperidiniaceans, it is also indicated that the motile stage of *P. fensomei* sp. nov. maintained a heterotrophic mode of life as evidenced by a lack of epifluorescence under ultraviolet light with a cyst that is darker than ambient slide illumination.

4.6 Acknowledgments

The Dr. Elaine Humphrey of the Advanced Microscopy Facility, University of Victoria (Victoria, British Columbia, Canada) is thanked for provided assistance with SEM micrograph rendering. The author also extends his gratitude to Dr. Jim Riding (British Geological Survey, Nottingham, U.K.), Dr. Martin Pearce (Evolution Applied Ltd, Wingrave, Buckinghamshire, U.K.), Dr. Peter Bijl (Utrecht University, Utrecht, the Netherlands) and an anonymous reviewer for their feedback which improved this manuscript. Funding for this project was provided by the National Science and Engineering Research Council (Canada), the Geological Society of America (U.S.A.), and the Paleontological Research Institute, Ithaka, New York, U.S.A.

Chapter 5

Calcareous dinoflagellate cyst distribution across the K/Pg boundary at DSDP Site 577, Shatsky Rise, western North Pacific Ocean¹

5.1 Contributions of authors

All of the content presented herein—the figures, data, analyses, results, discussions and conclusions—was produced by the lead author. In addition to providing assistance with the methodology and review of the manuscript, Dr. Vera Pospelova was instrumental in the conceptualization of this investigation.

5.2 Abstract

An analysis of calcareous dinoflagellate cysts has been carried out on sixteen samples from across the K/Pg boundary interval from Deep Sea Drilling Project Site 577 situated on Shatsky Rise in the western North Pacific. This is the first time that a detailed study of this microfossil group has been undertaken from deep sea sediments of Late Cretaceous–early Paleocene age in the North Pacific realm. Eight species of calcareous dinoflagellate cysts were found to comprise low diversity assemblages of which half are representative of extant taxa. The most pronounced bioevent is that of *Cervisiella operculata* reaching its highest proportions at the K/Pg boundary transition underscoring the utility and cosmopolitan distribution of the species with its acme as a marker for the earliest Danian. We also identify an indirect sea-surface paleotemperature signal

¹ This study was submitted to *Marine Micropaleontology* on June 22, 2021 as: McLachlan, S.M.S., Pospelova, V., Calcareous dinoflagellate cyst distribution across the K/Pg boundary at DSDP Site 577, Shatsky Rise, western North Pacific Ocean.

as represented by variance in wall thickness in two distinct morphotypes of *Thoracosphaera heimii* (morphotypes A and B). The cyst concentrations and relative abundances of these taxa are interpreted to reflect the late Maastrichtian cooling phase and subsequent interval of warming in the Danian marked by the opportunistic capitalization of *Cervisiella operculata* during a time of gradual phytoplankton recovery following the terminal Cretaceous.

5.3 Introduction

The end-Cretaceous extinction has been widely studied with a focus on the effects of the coinciding extraterrestrial bolide impact and Deccan volcanism on both marine and terrestrial ecosystems (e.g., Alegret et al., 2012; Vajda and Bercovici, 2014; Witts et al., 2016). The sensitivity of marine communities to the fallout of the K/Pg event throughout the world's oceans has been the subject of much attention as reflected in the plankton fossil record and a considerable volume of research has included foraminifera (e.g., Keller, 1989; Speijer and van der Zwaan, 1996; Culver, 2003; Koutsoukos, 2014; Woelders and Speijer, 2015; Woelders et al., 2017), calcareous nannofossils such as discoasters and coccoliths (e.g., Bramlette and Riedel, 1954; Edwards, 1966; Perch-Nielsen et al., 1982; Eshet et al., 1992; Moshkovitz and Habib, 1993; Egger et al., 2009) as well as calcitarchs (e.g., Kienel, 1994; Dias-Brito, 2000; Korbar et al., 2017). While these groups have proven to be valuable for biostratigraphy and resolving questions of paleoecology, it is perhaps the fossil record of dinoflagellate cysts that provides some of the most nuanced avenues of insight into phytoplankton community responsivity with their extensive capacity to elucidate paleoclimatic changes, indicate variance in ocean productivity levels and aid in paleoenvironmental reconstructions over the last ~200 myr (e.g., Fensome et al., 1996; Stover et al., 1996; Williams et al., 2004; Riding et al., 2010).

Among the organic-walled cyst producing dinoflagellates, a substantial body of literature demonstrates that the K/Pg event mainly resulted in quantitative fluctuations between ecogroups and perturbations among those species that were likely most sensitive to changes in global latitudinal temperature gradients (e.g., Brinkhuis and Zachariasse, 1988; Brinkhuis et al., 1998; Slimani et al., 2010, 2016; Guler et al., 2019; Chakir et al., 2020; Jbari et al., 2020; Soliman and Slimani, 2019; Vellekoop et al., 2015, 2019). The impact on calcareous cyst producing taxa was

somewhat greater, presented by the major decline of pithonelloid taxa and more measurable shifts in assemblage composition accentuated by overall lower diversity (e.g., Bramlette and Martini, 1964; Hildebrand-Habel et al., 1999; Wendler and Willems, 2002). Many taxa ranging from the Cretaceous to early Paleocene are present in modern sediments (e.g., Kohring et al., 2005) and the group is well represented in studies of oceanic settings and predominantly oligotrophic environments typified by lower productivity (Zonneveld et al., 2005) resulting in scarcity compared to organic-walled dinoflagellate cysts.

Palynological examination of the marine phytoplankton fossil record from the Late Cretaceous–early Paleocene in the North Pacific realm has been limited to studies of organic-walled dinoflagellate cyst taxa from wells in the East China Sea (Yu, 1989), the Nemuro Group (Kurita, 2004) and Haboro Formation (Kurita and Obuse, 1994, 1997) of Japan, the Nanaimo Group (McLachlan et al., 2018, 2019) and Oyster Bay Formation (McLachlan, 2021; McLachlan and Pospelova, 2021; McLachlan et al., 2021) of British Columbia and the Moreno Formation (Drugg, 1967) and Franciscan complex (Damassa, 1979a, 1979b) of California. All of these studies have considered assemblages reflective of highly productive offshore or neritic settings. Additionally, few surveys of calcareous dinoflagellate cysts have been conducted from similar age deep sea sediment cores in recent decades (e.g., South Atlantic Ocean: Hildebrand-Habel et al., 1999; Hildebrand-Habel and Willems, 2000; Streng et al., 2004b; Indian Ocean: Bernaola and Monechi, 2007) and taxonomic resolution of the Thoracosphaeraceae (Streng et al., 2004a; Elbrächter et al., 2008) presents the opportunity for refined application of this group.

During Leg 86 of the Deep Sea Drilling Project (DSDP), a series of holes were drilled at Site 577 on Shatsky Rise (Wright, 1985) (Fig. 5.1), the third largest oceanic plateau on Earth, located ~1500 km east of Japan in the northwestern Pacific Ocean (e.g., Sager, 2005) which has undergone a north-westward translation of 10° to 20° since the Cretaceous (e.g., Dickens and Backman, 2013; Jehle et al., 2015). Site 577 is located in the upper abyssal to lower bathyal zone at a depth of 2675 m below modern sea level; a position well above the calcite compensation depth allowing for the preservation of calcareous microfossils. Cores from Hole 577, drilled within ~100 m south of Hole 577A and the same distance to the north of Hole 577B, yielded a continuous, undisturbed sequence of white to light brown calcareous ooze (> 90% CaCO₃) across the K/Pg boundary interval (e.g., Wright et al., 1985; Gerstel et al., 1986; Zachos et al., 1989).

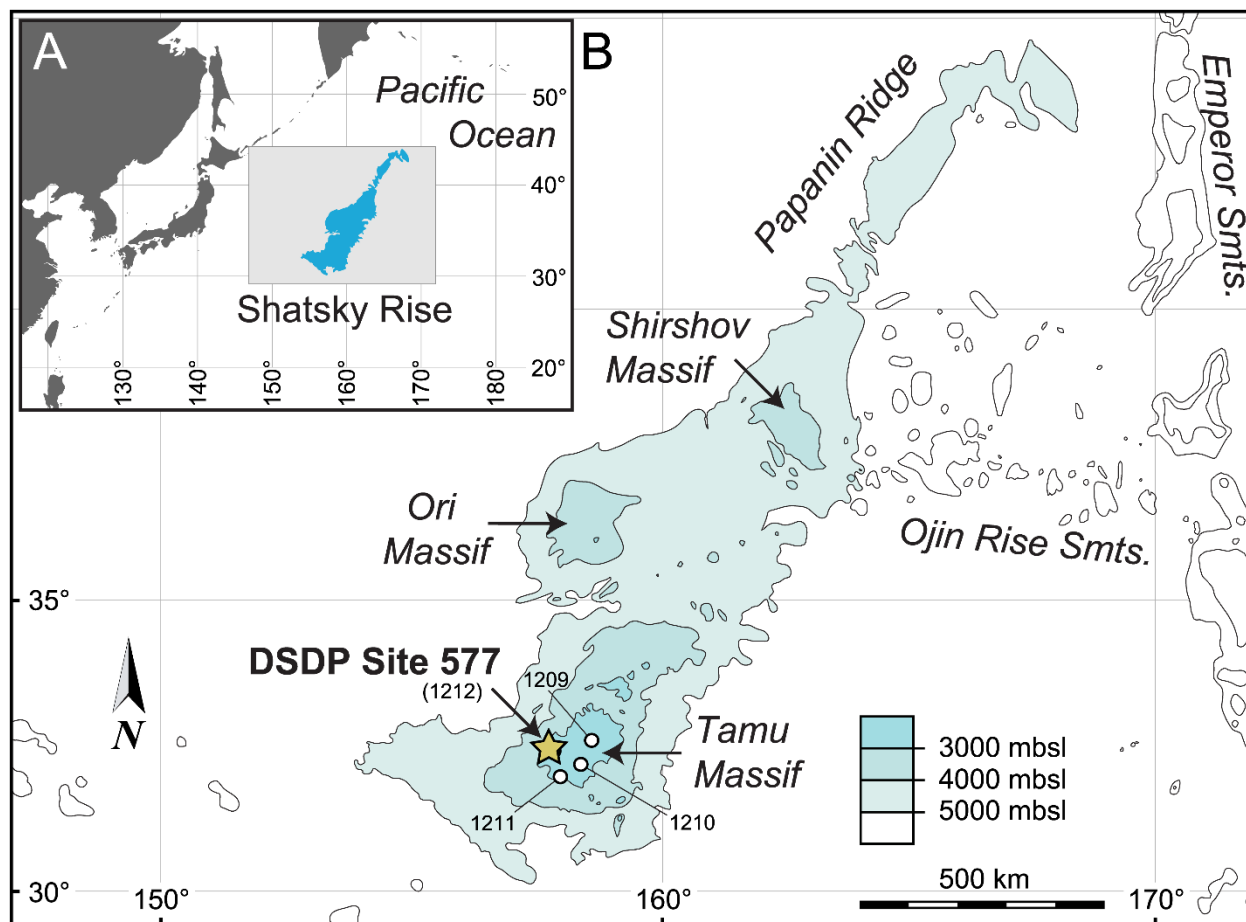


Figure 5.1. **A**, Location of Shatsky Rise (blue) in the northwestern Pacific Ocean. **B**, bathymetric map of Shatsky Rise after Sager (2005) with location (gold star) of Deep Sea Drilling Project Site 577 given by Wright et al. (1985). Locations of Ocean Drilling Program sites 1209–1212 (white points) plotted after Bown (2005b).

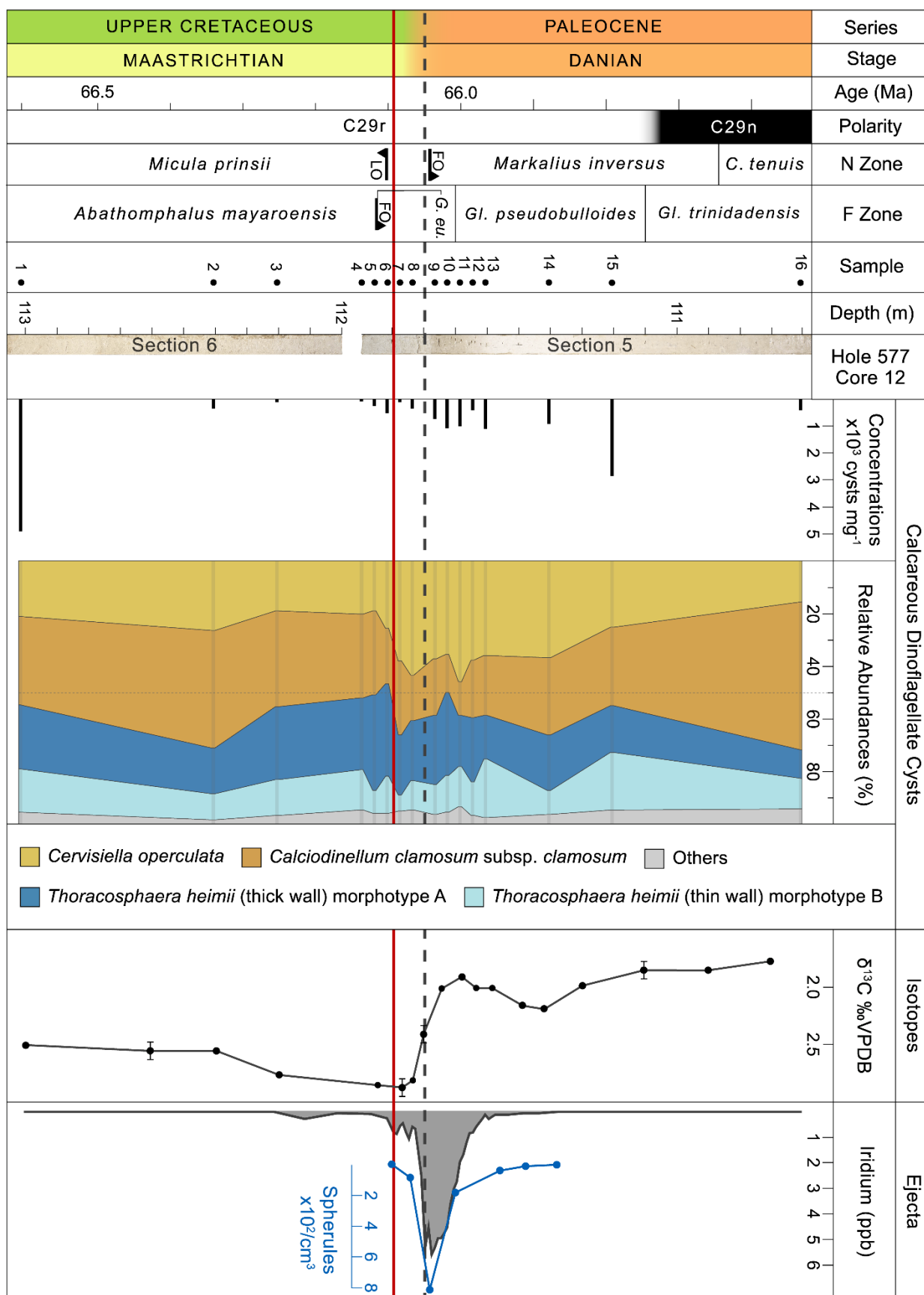
This lack of disturbance stands in contrast to those recovered during Leg 198 of the Ocean Drilling Program (ODP) at sites 1209 to 1212 from Shatsky Rise which record considerable nannofossil reworking and sediment bioturbation (e.g., Bralower et al., 2002; Bown, 2005a; Premoli Silva et al., 2005; Alegret and Thomas, 2009) (Fig. 5.1). The high quality of the undisturbed sequence at Site 577 is the basis for the core material having been selected for this study.

5.4 Materials and methods

A total of sixteen samples were processed to extract calcareous dinoflagellate cysts from within 2.4 m across the K/Pg boundary interval corresponding to the sections obtained from cores 5 and 6 from Hole 12 of Site 577. Subsamples were found to be virtually barren of organic-walled dinoflagellate cysts after preparation using a standardized palynological procedure (e.g., Pospelova et al., 2010). The rest of the sedimentary material was then processed to enable analysis of calcareous dinoflagellate cysts. For each of the samples, subsamples of calcareous ooze were placed in 15 ml polypropylene test tubes with the dry weights of these samples averaging ~1.2 g. A single *Lycopodium clavatum* tablet of batch #3862 ($9,666 \pm 671$ spores per tablet, produced at the Department of Geology, University of Lund, Lund, Sweden) was added to each sample to estimate absolute cyst abundances (e.g., Benninghoff, 1962; Stockmarr, 1971; Mertens et al., 2009b, 2012c). Three drops of ammonium hydroxide were added to the reverse osmosis water in each subsample test tube to prevent carbonate dissolution and let sit for 24 h.

Once the size range of the taxa present was confirmed, sieving took place through a 63 μm mesh to remove large foraminiferal tests and the fraction above a 15 μm mesh was retained. The samples underwent up to 30 sec of ultrasonic agitation (Mertens et al., 2012c) to dislodge any minute sediment particles from the dinoflagellate cysts and centrifuging at 3600 rpm for 6 min prior to decanting. Following sieving, residue was mounted in glycerin jelly on microscope slides for bright-field microscopy. Unless otherwise stated, all microfossil samples are housed within the Department of Earth and Environmental Sciences, University of Minnesota, (Minneapolis, Minnesota, USA) and Advanced Microscopy Facility, University of Victoria, (Victoria, British Columbia, Canada). Calcareous dinoflagellate cyst identification and counts were conducted at 1000x magnification wherein a single specimen was recorded if more than half its structure was intact (operculum notwithstanding). Counts of at least 200 calcareous dinoflagellate cysts were reached for each sample as to ensure a statistically sufficient number for relative and absolute abundance calculations; a number exceeding that deemed sufficient for even higher diversity K/Pg assemblages (e.g., Hildebraiid-Habel and Willems, 2000; Hildebrand-Habel et al., 1999).

Bright-field photomicrographs were taken under 1000x magnification with a Nikon DS-5M-L1 digital camera system mounted on a Nikon Eclipse 80i light microscope. For clarity of image



← **Figure 5.2.** Schematic framework for the stratigraphic sections of Deep Sea Drilling Project Site 577, Hole 577, Core 12 (Shatsky Rise, northwestern Pacific Ocean) with plotted sample locations, calcareous dinoflagellate cyst concentrations and relative abundances across the K/Pg boundary interval. Depth of the sections below the sea floor follows the correction of Dickens and Backman (2013). N Zone = nannofossil zones of Monechi (1985) and Monechi et al. (1985) where *C.* is *Cruciplacolithus*. F Zone = foraminiferal zones of Gerstel et al. (1986) where *G. eu.* is *Globigerina eugubina* and *Gl.* is *Globorotalia*. FO = first occurrence of eponymous zonal taxon. LO = last occurrence of eponymous zonal taxon. Magnetostratigraphy after Bleil (1985). Carbonate isotope data from Zachos et al. (1985). Iridium concentration data after Michel et al. (1985) interpolated from Hole 577B, Core 1. Spherule concentration data after Gerstel et al. (1986). Dashed line corresponds to the K/Pg boundary as interpreted by Monechi (1985) and Monechi et al. (1985). Red line denotes the boundary between the intervals of *Thoracosphaera heimii* morphotype A and *Cervisiella operculata* peak relative abundances.

presentation, extraneous particulate debris were removed from the field of view (Riding and Head, 2018) with a brush tool using Macromedia Fireworks 8 software if the material was not in contact with the specimen ambitus. Specimens prepared for scanning electron microscopy (SEM) underwent an additional 15 sec of ultrasonic agitation during sieving prior to being transferred to aluminum SEM stubs with a micropipette. SEM stubs were then coated with a gold/palladium mix using an Anatech Hummer VI sputter coater for a thickness of 20–30 nm. Micrographs of selected specimens were taken using a Hitachi S-4800 SEM at the Advanced Microscopy Facility (University of Victoria, Victoria, Canada) with post-production black level adjustments and unsharp masking. The approach to classification and nomenclature follows that of Elbrächter et al. (2008) and Fensome et al. (2019). The conventional Kofoed Tabulation System (Kofoed, 1907a, 1907b, 1909, 1911) is employed in plate identification in light of Streng et al. (2004a). Terminology pertaining to classes of relative abundance follow the parameters of Pospelova et al. (2004): present (>0–1%); rare (>1–5%); common (>5–30%); abundant (>30–50%); dominant (>51%).

5.5 Results

5.5.1 Marine palynology

Although largely barren of organic-walled dinoflagellate cysts, the core samples yielded eight species of calcareous dinoflagellate cysts belonging to at least six genera. The following taxa were observed, all of which are seen across the K/Pg boundary interval: *Calciodinellum clamosum* subsp. *clamosum* Streng et al., 2004a (Plate 5.1, figs. 1–12), *Calciodinellum elongatum* (Hildebrand-Habel et al., 1999) Streng et al., 2006 (Plate 5.2, figs. 1–3), *Cervisiella operculata* (Bramlette and Martini, 1964) Streng et al., 2004a (Plate 5.3, figs. 1–12), *Feuttererella tesserula* (Fütterer, 1978) Kohring, 1993 (Plate 5.2, figs. 4–7), *Pernambugia tuberosa* (Kamptner, 1963) Janofske and Karwath, 2000 (Plate 5.6, figs. 1–9), *Pirumella edgarii* (Bolli, 1974) Lentin and Williams, 1993 (Plate 5.6, figs. 10–12), *Thoracosphaera heimii* (Lohmann, 1920) Kamptner, 1944 morphotype A (Plate 5.4, figs. 1–12), *Thoracosphaera heimii* (Lohmann, 1920) Kamptner, 1944 morphotype B (Plate 5.5, figs. 1–9) and Cyst Type A, a form characterized by irregular, coarse granulate to vermiculate surface ornament (Plate 5.2, figs. 8–12). Cyst concentrations range from 12 to 490 cysts mg⁻¹, undergoing a slight decrease prior to an upward increasing trend above Sample 7 (Fig. 5.2). Specimen counts and abundance data are presented in Table 5.1 as well as Appendix 4.A.

Thoracosphaera heimii is the largest constituent of the assemblages maintaining strong representation throughout the section ranging from 22.5 to 49.1% (avg. 37.2); from samples 1 through 6, its greatest proportions are seen averaging 41% before declining somewhat with an overall average of 34.9% from samples 7 to 16 (Fig. 5.2; Table 5.1). *Thoracosphaera heimii* morphotype A averages 20.9% below Sample 3 prior to increasing to higher levels ranging from 27.2 to 36.6% (avg. 31.6%) in samples 3 through 6, before returning to somewhat lower percentages up-section at 21.3% on average. Proportions of *T. heimii* morphotype B average 13.4% of the assemblages and are relatively consistent throughout the interval with minor fluctuations. *Cervisiella operculata* (avg. 30.2%) exhibits the most dramatic change across the K/Pg boundary interval. Relative abundances of the species range from 18.6 to 26.7% (avg. 22%) in samples 1 through 6, prior to presenting a nearly two fold increase from samples 7 to 14. At ~111.9 mbsf, there is a marked shift from the species reaching just over one quarter of the assemblages in the latest Maastrichtian to consistently representing over one third of the assemblages in the earliest Danian ranging from 35.6 to 46% (avg. 38.8%), before decreasing to previous levels again above Sample 14 (avg. 20.5%) (Fig. 5.2; Table 5.1). *Calciodinellum*

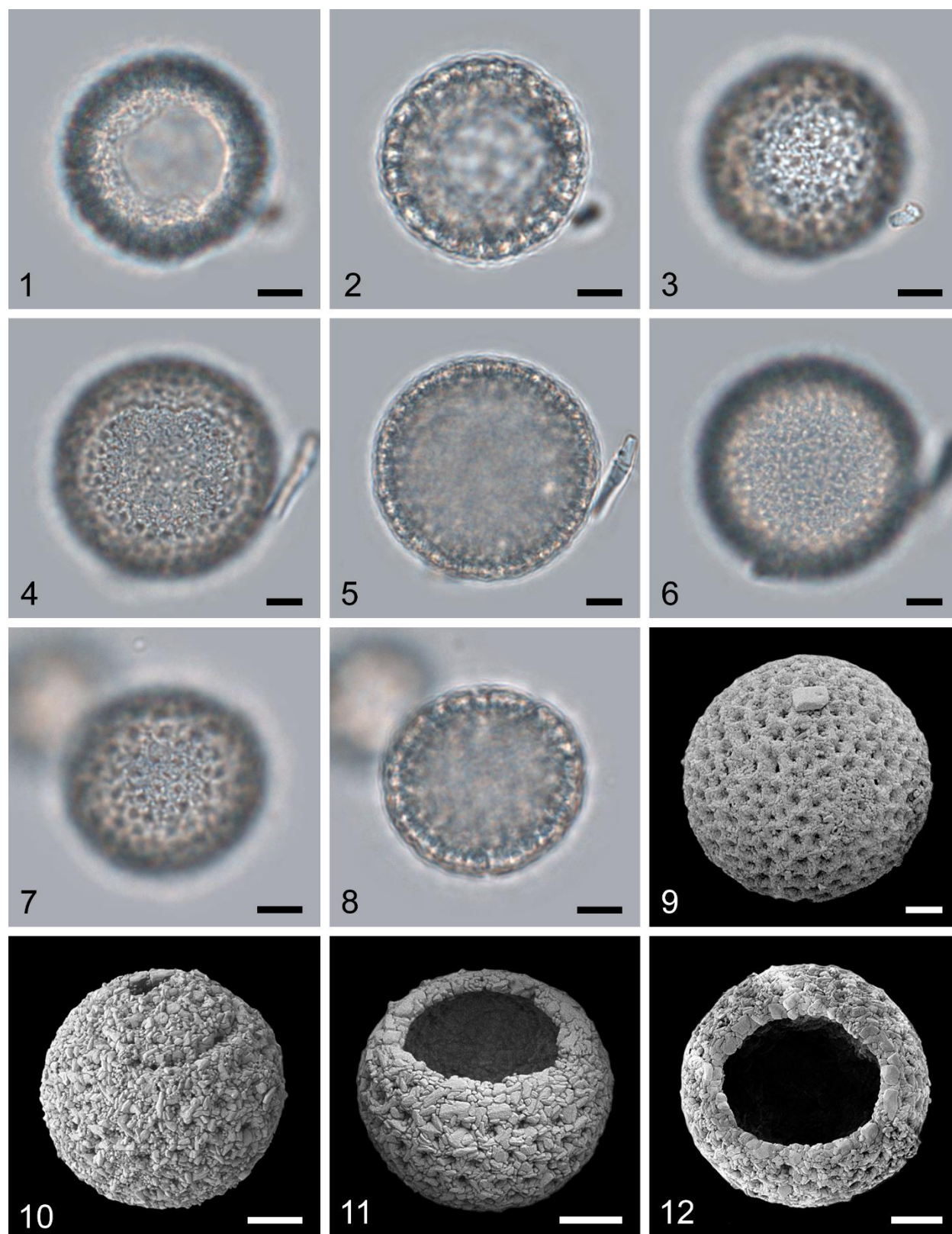


Plate 5.1. Bright-field photomicrographs and scanning electron micrographs of the calcareous dinoflagellate cyst *Calciadinellum clamosum* subsp. *clamosum* Streng et al., 2004a collected from core

sediments recovered from Deep Sea Drilling Project Site 577, Shatsky Rise, northwestern Pacific Ocean. 1–3, specimen without operculum, Sample 3, 112.21 mbsf (UVic 2020-3, slide B, EF G37/4); 1, apical view, archeopyle in focus; 2, mid focus; 3, antapical view. 4–6, specimen with operculum in place, Sample 3, 112.21 mbsf (UVic 2020-3, slide B, EF E29/0); 4, apical view with archeopyle margin in focus; 5, mid focus; 6, antapical view. 7, 8, specimen with operculum in place, Sample 13, 111.61 mbsf (UVic 2020-13, slide A, EF H37/1); 7, lateral view; 8, mid focus. 9, specimen from Sample 2, 112.41 mbsf (UVic 2020-2, stub Se), antapical view. 10, specimen with operculum in place, Sample 2, 112.41 mbsf (UVic 2020-2, stub Se), apicolateral view. 11, specimen without operculum, Sample 2, 112.41 mbsf (UVic 2020-2, stub Se), apicolateral view. 12, specimen without operculum, Sample 15, 111.21 mbsf (UVic 2020-15, stub Sb), apical view. Scale bars = 5 μ m.

clamosum subsp. *clamosum* is the third largest assemblage constituent averaging 28.2% throughout the interval. From samples 1 through 6, the species ranges from 21.2 to 41.2% (avg. 33%) falling to percentages ranging from 14.2 to 29.6% (avg. 21.9%) in samples 7 through 15. Only in the highest Danian sample, taken above 110.61 mbsf, does *C. c.* subsp. *clamosum* dominate at 56%. All other species are generally rare outliers seldom exceeding 5% of the assemblages when combined, ranging from 1.9 to 6.6%. The proportions of these taxa present no discernable trends, although Cyst Type A curiously attains 3.3% in Sample 1 only to become scarce across the K/Pg boundary interval before returning to a comparable level (4.3%) in Sample 16. It is at the juncture between samples 6 and 7 that we observe a clear assemblage reconfiguration based on the onset of elevated percentages of *Cervisiella operculata* following an abrupt transition bridging intervals of higher and lower proportions of *Thoracosphaera heimii* morphotype A moving upward in the section (Fig. 5.2; Table 5.1).

5.5.2 Systematic paleontology

Division: DINOFLAGELLATA (Bütschli, 1885) Fensome et al., 1993

Subdivision: DINOKARYOTA Fensome et al., 1993

Class: DINOPHYCEAE Pascher, 1914

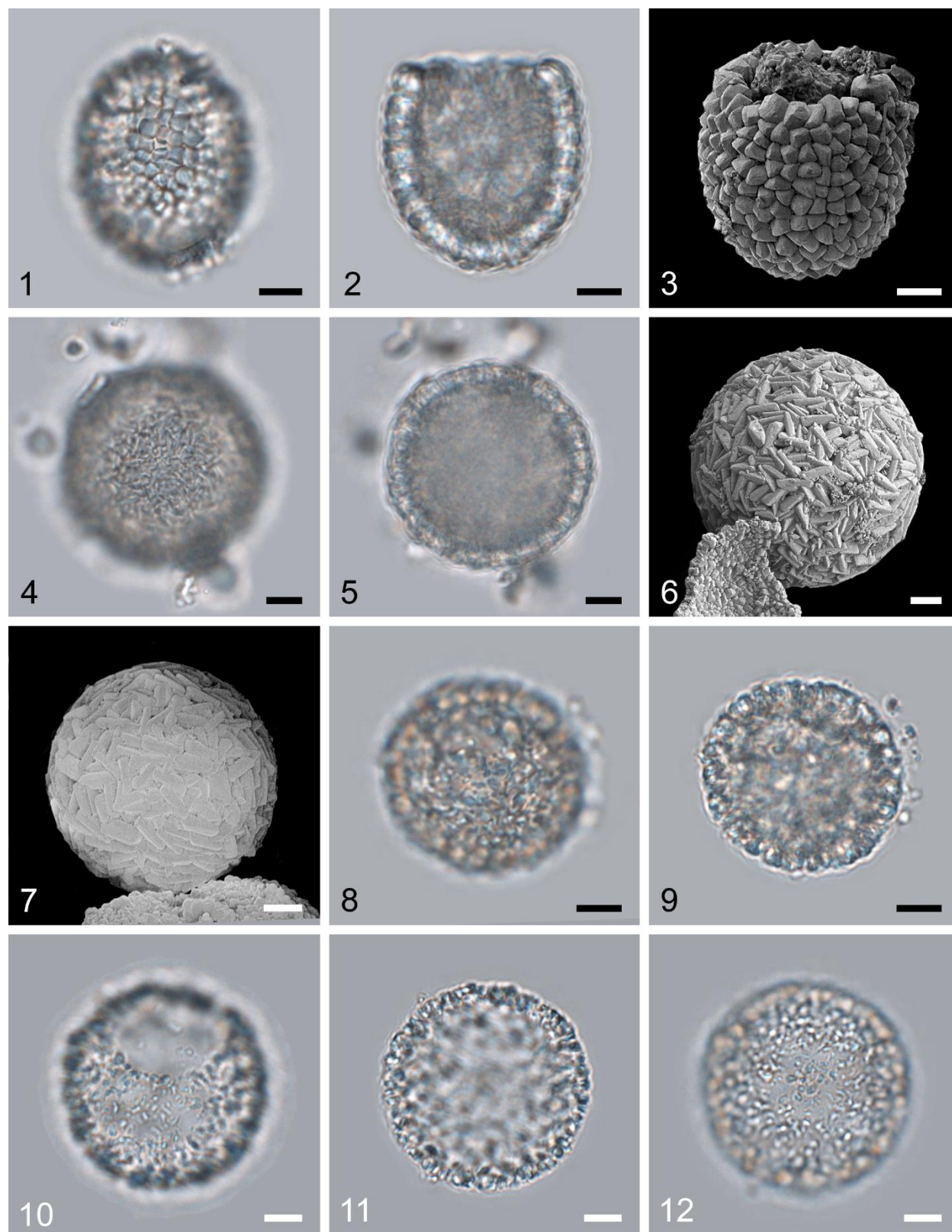


Plate 5.2. Bright-field photomicrographs and scanning electron micrographs of selected calcareous dinoflagellate cysts collected from core sediments recovered from Deep Sea Drilling Project Site 577,

Shatsky Rise, northwestern Pacific Ocean. 1–3, *Calciadinellum elongatum* (Hildebrand-Habel et al., 1999) Streng et al., 2006; 1, specimen with operculum in place, lateral view, Sample 4, 111.99 mbsf (UVic 2020-4, slide A, EF K30/1); 2, specimen without operculum, mid focus, Sample 4, 111.99 mbsf (UVic 2020-4, slide A, EF N33/0); 3, specimen with calcareous debris infill, lateral view, Sample 2, 112.41 mbsf (UVic 2020-2, stub Sa). 4–7, *Feuttererella tesserula* (Fütterer, 1978) Kohring, 1993; 4, 5, specimen from Sample 2, 112.41 mbsf (UVic 2020-2, slide A, EF F47/2); 4, antapical view; 5, mid focus; 6, specimen from Sample 2, 112.41 mbsf (UVic 2020-2, stub Sa), antapical view; 7, specimen from Sample 2, 112.41 mbsf (UVic 2020-2, stub Sg), antapical view. 8–12, Cyst Type A; 8, 9, specimen without operculum, Sample 4, 111.99 mbsf (UVic 2020-4, slide A, EF Q25/4); 8, apicolateral view; 9, mid focus; 10–12, specimen without operculum, Sample 16, 109.61 mbsf (UVic 2020-16, slide A, EF C26/4); 10, apicolateral view; 11, mid focus; 12, antapicolateral view. Scale bars = 5 μ m.

Subclass: PERIDINIPHYCIDA Fensome et al., 1993

Order PERIDINIALES Haeckel, 1894

Suborder PERIDINIINEAE (autonym)

Family: THORACOSPHAERACEAE Schiller, 1930

Genus: **THORACOSPHAERA** (Kamptner, 1927) Fütterer, 1976

Thoracosphaera heimii (Lohmann, 1920) Kamptner, 1944

Remarks. Tangen et al. (1982) demonstrated that the calcareous tests of *Thoracosphaera heimii* represent structures of the vegetative life stage and are not actually resting cysts making them unique among members of the Thoracosphaeraceae (Elbrächter et al., 2008). Specimens of *T. heimii* recovered from the Site 577 core are slightly diagenetically altered such that their crystal elements have been smoothed and thickened by calcite overgrowth, but not exclusively to the extent that the original mid-platelet poroids are entirely infilled, as evidenced by the occasional presence of subtle depressions (Plate 5.4, fig. 11). These minute depressions, in combination with an overall blocky appearance, lend these cysts to bear a superficial similarity to *Priumella ossa* (Kienel, 1994) Williams et al., 1998 which differs in having steeper relief of the angular elements on its interlocking platelets along with a much larger archaeopyle defined by zig-zag margins. The same form of diagenetic alteration observed in *T. heimii* at Site 577 was

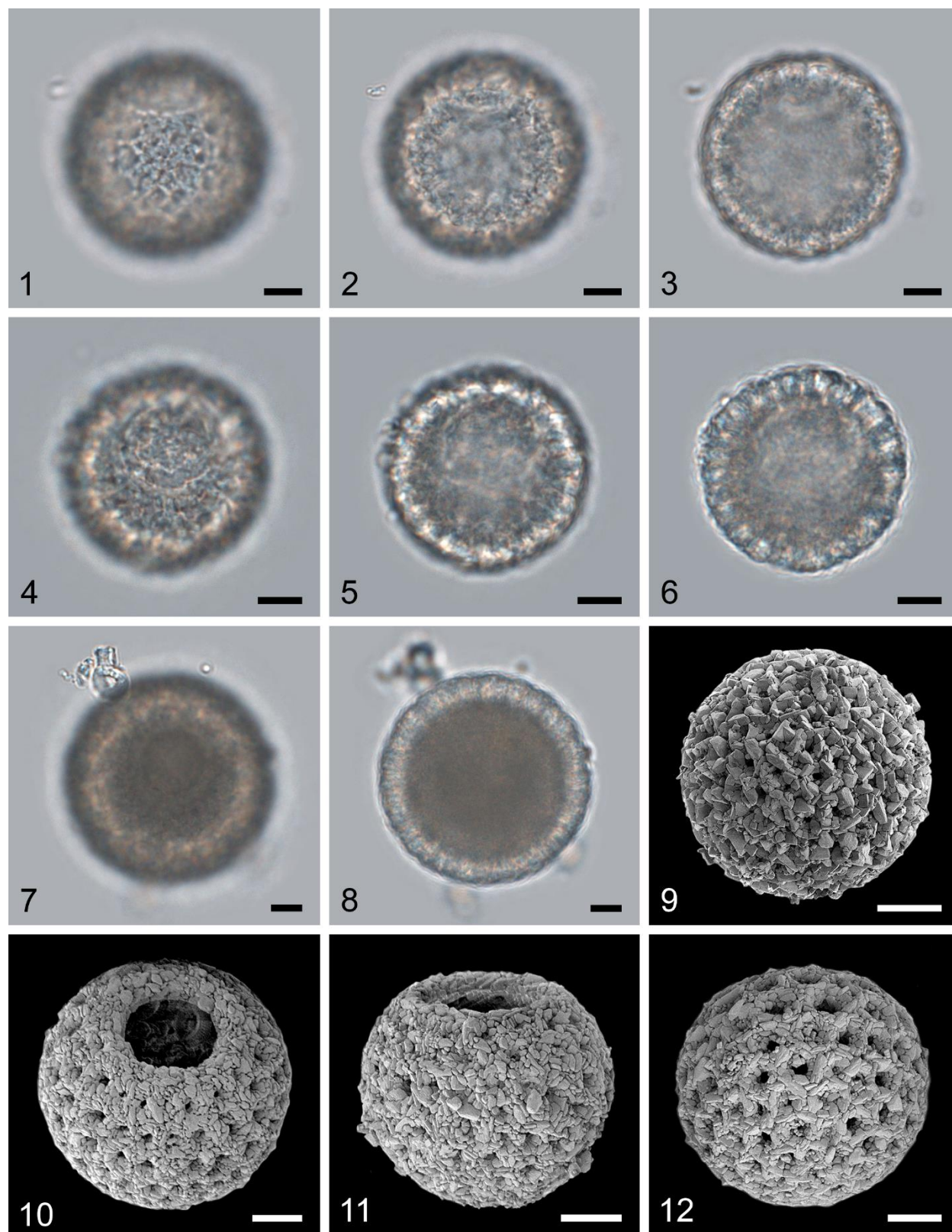


Plate 5.3. Bright-field photomicrographs and scanning electron micrographs of the calcareous dinoflagellate cyst *Cervisiella operculata* (Bramlette and Martini, 1964) Streng et al., 2004a collected

from core sediments recovered from Deep Sea Drilling Project Site 577, Shatsky Rise, northwestern Pacific Ocean. 1–3, specimen with operculum in place, Sample 13, 111.61 mbsf (UVic 2020-13, slide A, EF G38/3); 1, lateral view; 2, one-quarter focus; 3, mid focus. 4–6, specimen with operculum in place, Sample 4, 111.99 mbsf (UVic 2020-4, slide A, EF H41/4); 4, oblique apical view; 5, one-quarter focus; 6, mid focus. 7, 8, specimen without operculum from Sample 4, 111.99 mbsf (UVic 2020-4, slide A, EF O32/2); 7, apical view; 8, mid focus. 9, specimen from Sample 15, 111.21 mbsf (UVic 2020-15, stub Sb), antapical view. 10, specimen without operculum, Sample 2, 112.41 mbsf (UVic 2020-2, stub Sa), apicolateral view. 11, specimen without operculum, Sample 2, 112.41 mbsf (UVic 2020-2, stub Se), lateral view. 12, specimen from Sample 2, 112.41 mbsf (UVic 2020-2, stub Se), antapicolateral view. Scale bars = 5 μ m.

first reported by Fütterer (1978, pl. 1, figs. 7–12) following his observation of smoothed surface relief and poroid infill in specimens collected from Miocene sediments at Sierra Leone Rise, DSDP Site 366. His conclusion of diagenetic alteration as a process having acted upon these specimens resulted in subsequent invalidation of *Thoracosphaera imperforata* Kamptner, 1955 (Fütterer, 1978). Fütterer (1978) further emphasized the sensitivity of *T. heimii* to alteration via secondary calcite overgrowth in relation to other calcareous microfossils at burial depths in excess of 80 m. Furthermore, following analysis of exceptionally well preserved Cretaceous thoracosphaeracean tests, Wendler and Bown (2013) surmised that potentially all pithonellid-type taxa are subject to significant recrystallization during diagenesis such that the original ultrastructure is essentially obscured. Prior to this study, the oldest material was described only from poorly preserved specimens from the upper Maastrichtian deposits of DSDP Site 356 in the South Atlantic (Hildebrand-Habel et al., 1999), but the authors did not provide comment as to whether or not their state was reflective of diagenetic alteration. Given the level of alteration in the present material, we refrain from proposing a formal emendation to the diagnosis of *T. heimii* reflecting uncertainty surrounding our interpretation of an original archaeopyle corresponding to the formula $A_{2-4'}$, however probable.

***Thoracosphaera heimii* morphotype A**

Plate 5.4, figs. 1–12

1955 *Thoracosphaera imperforata* Kamptner, p. 37, 66–71; pl. 8, fig. 98.

1963 *Thoracosphaera imperforata* (Kamptner) Kamptner, p. 179; pl. 5, figs. 29, 31.

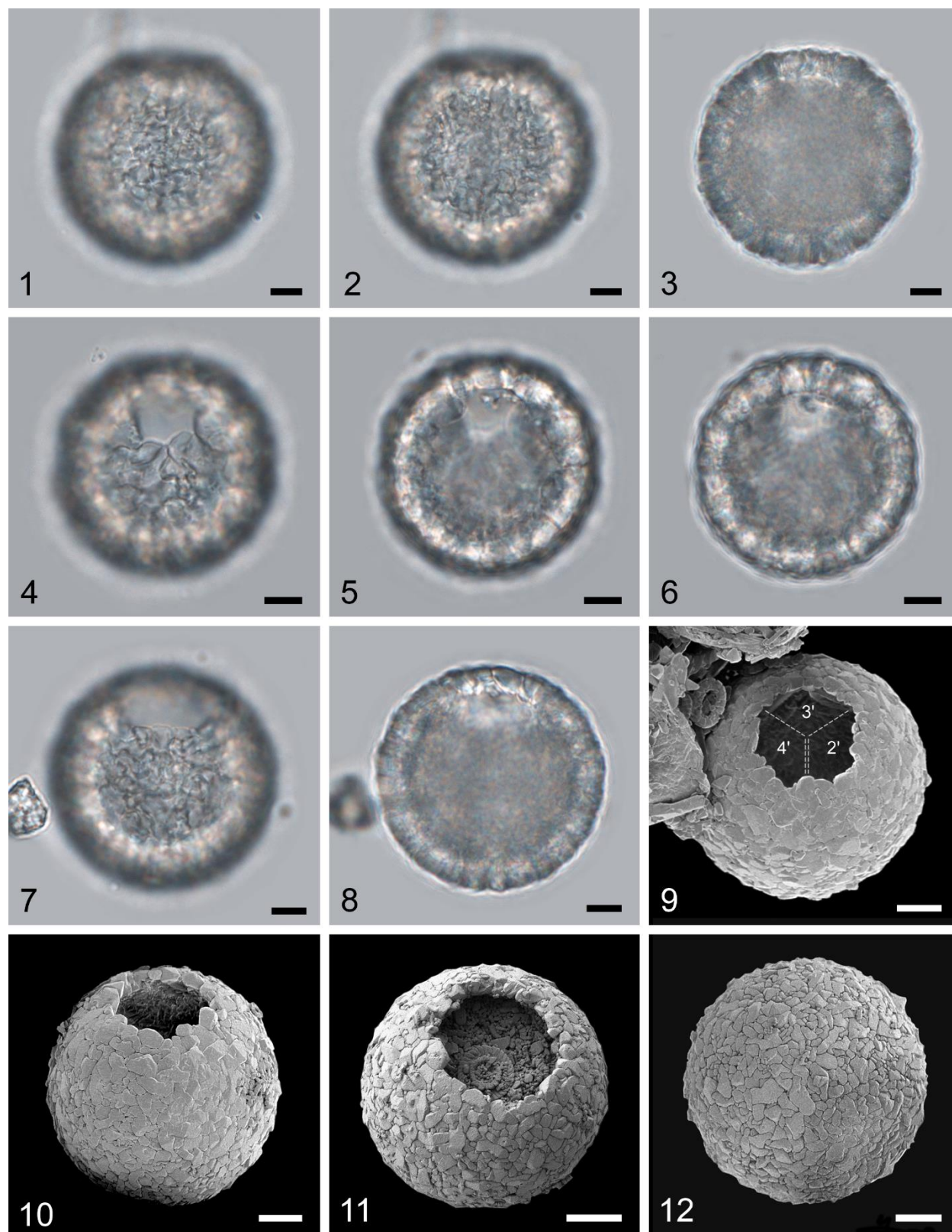


Plate 5.4. Bright-field photomicrographs and scanning electron micrographs of the calcareous dinoflagellate cyst *Thoracosphaera heimii* (Lohmann, 1920) Kamptner, 1944 morphotype A collected

from core sediments recovered from Deep Sea Drilling Project Site 577, Shatsky Rise, northwestern Pacific Ocean. 1–3, specimen without operculum, Sample 3, 112.21 mbsf (UVic 2020-3, slide A, EF J34/0); 1, lateral view; 2, one-quarter focus; 3, mid focus. 4–6, specimen without operculum, Sample 3, 112.21 mbsf (UVic 2020-3, slide B, EF F37/4); 4, lateral view; 5, one-quarter focus; 6, mid focus. 7, 8, specimen without operculum, Sample 9, 111.77 mbsf (UVic 2020-9, slide A, EF C33/1); 7, lateral view; 8, mid focus. 9, specimen without operculum from Sample 2, 112.41 mbsf (UVic 2020-2, stub Sf), apical view with inferred archeopyle tabulation. 10, specimen without operculum from Sample 2, 112.41 mbsf (UVic 2020-2, stub Sg), lateral view. 11, specimen without operculum from Sample 2, 112.41 mbsf (UVic 2020-S, stub Se), apicolateral view. 12, specimen from Sample 2, 112.41 mbsf (UVic 2020-2, stub Sg), antapical view. Scale bars = 5 μm .

1964 *Thoracosphaera* cf. *T. imperforata* (Kamptner) Bramlette & Martini, p. 305; pl. 5, figs. 1, 2.

?1965 ?*Thoracosphaera imperforata* (Kamptner) Cohen, p. 31; pl. 5, fig. g.

1978 *Thoracosphaera heimii* (Lohmann) Kamptner; Fütterer, p. 713, 714; pl. 1, figs. 7–12.

Description. A *Thoracosphaera heimii* morphotype characterized by diagenetic alteration of the spherical test wherein calcite overgrowth has resulted in ornamental poroid infill and thickening of the crystal platelets as to render the wall $\geq 2 \mu\text{m}$ in thickness with a wall thickness-to-diameter ratio typically >0.10 . Both inner and outer surfaces of the single-layered wall present as a mosaic of irregularly sized, blocky to acutely angular crystals forming platelets of low surface relief. The platelets are often disjunct and offset in relation to one another along their contacts. On their exterior surface, platelets are occasionally punctuated by centralized notches or depressions indicative of relict ornamental poroids. Archaeopyle polyplacoid(?) apical, operculum free, presumably formed from the loss of plates 2'–4' as inferred from the marginal outline with indication of apically directed tip of plate 1' and by extension, incisions at 2'–3'–1a and 3'–4'–3a triple junctions (Plate 5.4, fig. 9).

Dimensions. Diameter (D): 20 (26.2) 34.7 μm , number of specimens: 39. Wall thickness (Wt): 2 (3) 4.4 μm , number of specimens: 39. Wt/D: 0.08 (0.12) 0.17. Archeopyle width: 4.7 (9.5) 13.4 μm , number of specimens: 31. Measurements obtained from specimens analyzed through transmitted light microscopy are listed in Appendix 4.B, Table 1, along with their respective England Finder (EF) coordinates. The coordinates are taken with the slide label to the right.

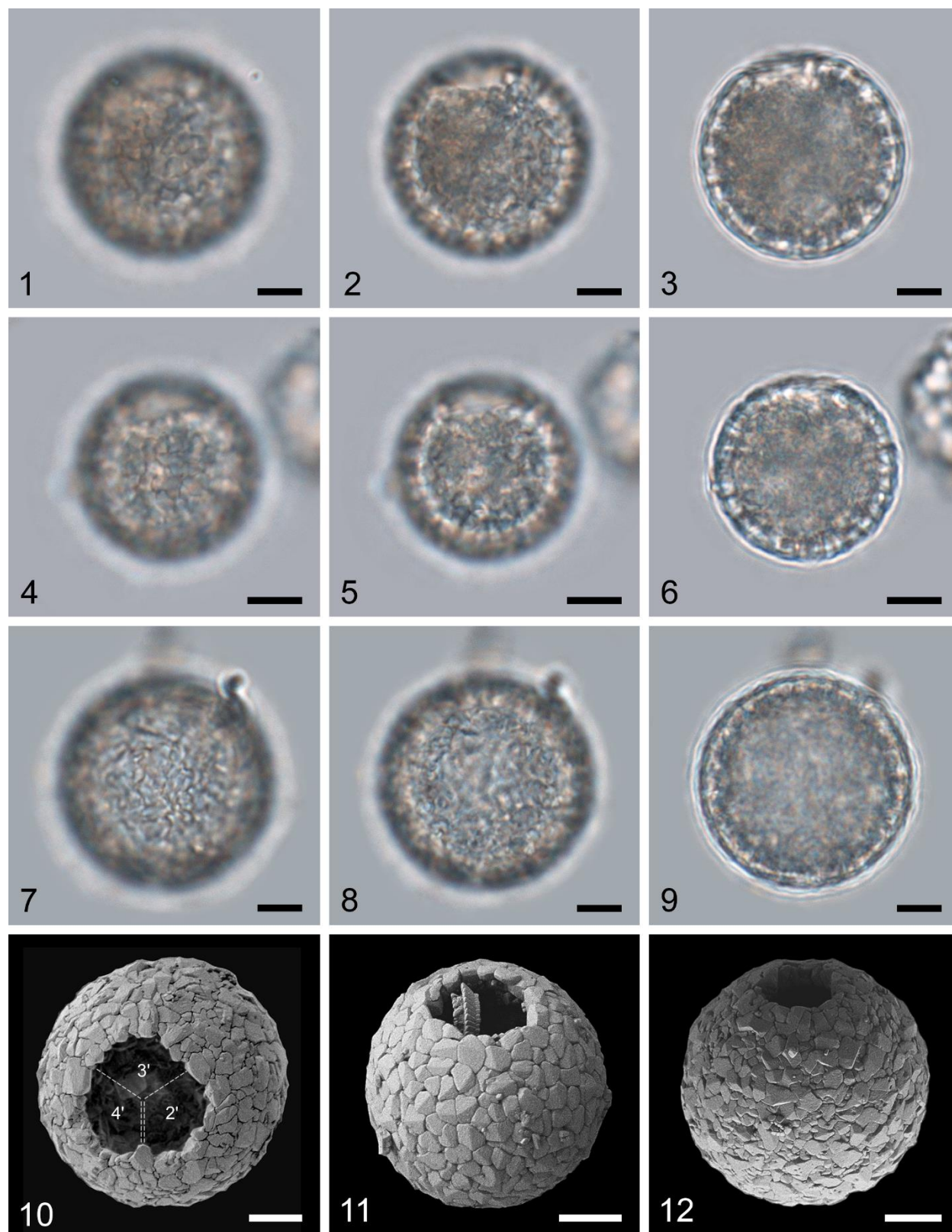


Plate 5.5. Bright-field photomicrographs and scanning electron micrographs of the calcareous dinoflagellate cyst *Thoracosphaera heimii* (Lohmann, 1920) Kamptner, 1944 morphotype B collected

from core sediments recovered from Deep Sea Drilling Project Site 577, Shatsky Rise, northwestern Pacific Ocean. 1–3, specimen without operculum, Sample 3, 112.21 mbsf (UVic 2020-3, slide B, EF J27/0); 1, lateral view; 2, one-quarter focus; 3, mid focus. 4–6, specimen without operculum, Sample 5, 111.96 mbsf (UVic 2020-5, slide A, EF M23/0); 4, lateral view; 5, one-quarter focus; 6, mid focus. 7–9, specimen with operculum in place, Sample 5, 111.96 mbsf (UVic 2020-5, slide A, EF N41/3); 7, lateral view; 8, one-quarter focus; 9, mid focus. 10, specimen without operculum from Sample 2, 112.41 mbsf (UVic 2020-2, stub Se), apical view with inferred archeopyle tabulation. 11, specimen without operculum from Sample 2, 112.41 mbsf (UVic 2020-2, stub Sf), lateral view, note coccolith inset within archeopyle. 12, specimen without operculum from Sample 2, 112.41 mbsf (UVic 2020-2, stub Sf), lateral view. Scale bars = 5 μm .

Comparison. *Thoracosphaera heimii* morphotype A differs from unaltered cysts of the species by the distinct calcite infill of its ornamental poroids and extensive crystal overgrowth smoothing the appearance of its original surface elements. In contrast to *T. h.* morphotype B, *T. h.* morphotype A possesses a thicker wall ($\geq 2 \mu\text{m}$ thick) and a wall thickness-to-diameter ratio generally > 0.10 . The latter subspecies also bears a larger cyst diameter of $\geq 20 \mu\text{m}$ on average.

***Thoracosphaera heimii* morphotype B**

Plate 5.5, figs. 1–12

1999 *Thoracosphaera heimii* (Lohmann) Kamptner; Hildebrand-Habel et al., pl. 6, figs. 19, 20.

Description. A *Thoracosphaera heimii* morphotype characterized by diagenetic alteration of the spherical test wherein calcite overgrowth has resulted in ornamental poroid infill and thickening of the crystal platelets as to render the wall $< 2 \mu\text{m}$ in thickness with a wall thickness-to-diameter ratio typically < 0.10 . Both inner and outer surfaces of the single-layered wall present as a mosaic of irregularly sized, blocky to acutely angular crystals forming platelets of low surface relief. The platelets are often disjunct and offset in relation to one another along their contacts. On their exterior surface, platelets are occasionally punctuated by centralized notches or depressions indicative of relict ornamental poroids. Archaeopyle polyplacoid(?) apical, operculum free, presumably formed from the loss of plates 2'–4' as inferred from the marginal outline with indication of apically directed tip of plate 1' and by extension, incisions at 2'–3'–1a and 3'–4'–3a triple junctions (Plate 5.5, fig. 10).

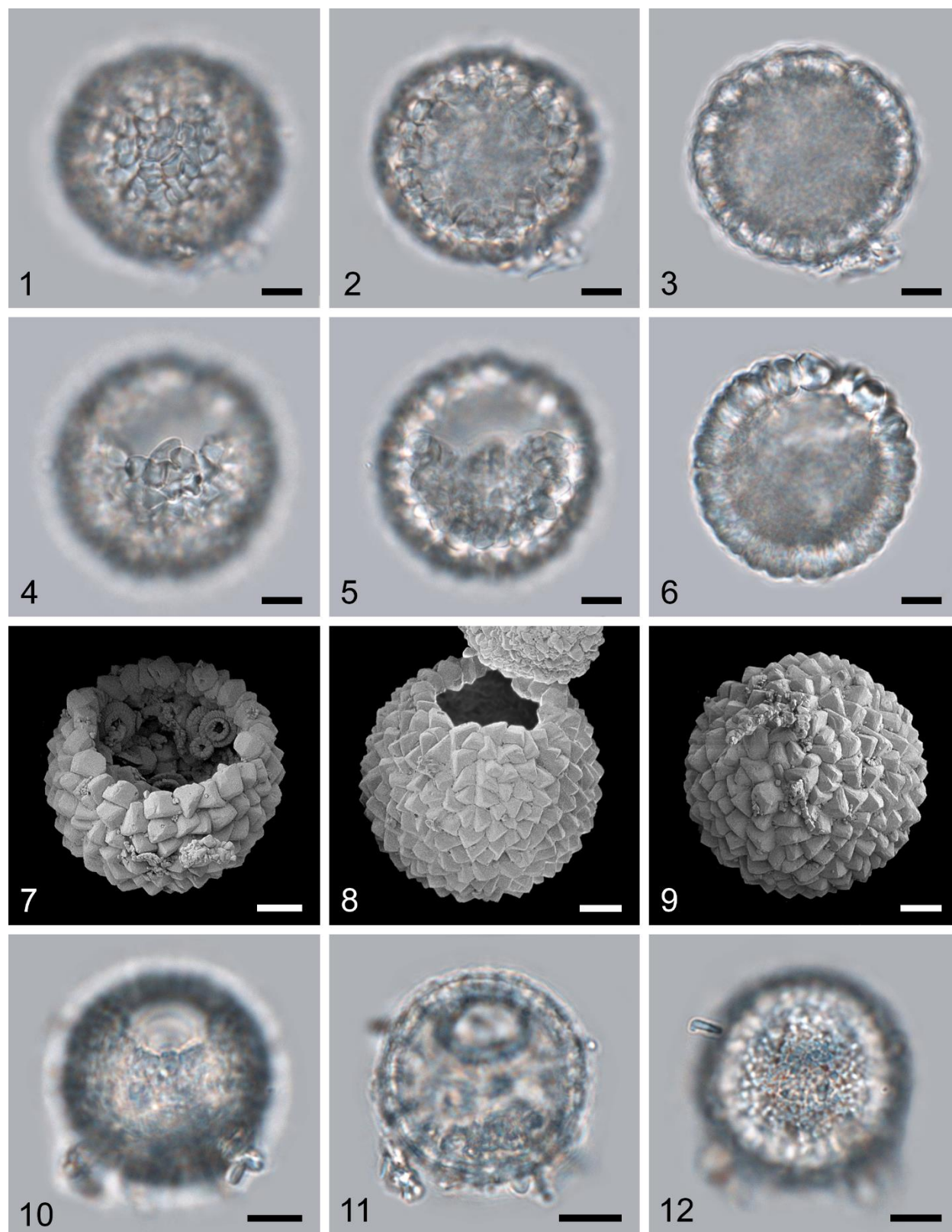


Plate 5.6. Bright-field photomicrographs and scanning electron micrographs of selected calcareous dinoflagellate cysts collected from core sediments recovered from Deep Sea Drilling Project Site 577,

Shatsky Rise, northwestern Pacific Ocean. 1–9, *Pernambugia tuberosa* (Kamptner, 1963) Janofske and Karwath, 2000; 1–3, specimen with operculum in place, Sample 5, 111.96 mbsf (UVic 2020-5, slide A, EF H31/0); 1, lateral view; 2, one-quarter focus; 3, mid focus. 4–6, specimen without operculum, Sample 9, 111.77 mbsf (UVic 2020-9, slide A, EF G34/0); 4, lateral view; 5, one-quarter focus; 6, mid focus. 7, specimen without operculum from Sample 2, 112.41 mbsf (UVic 2020-2, stub Se), apicolateral view. 8, specimen without operculum from Sample 2, 112.41 mbsf (UVic 2020-2, stub Sg), lateral view. 9, specimen from Sample 2, 112.41 mbsf (UVic 2020-2, stub Se), antapical view. 10–12, *Pirumella edgarii* (Bolli, 1974) Lentin and Williams, 1993, specimen without operculum, Sample 2, 112.41 mbsf (UVic 2020-2, slide A, EF V41/2); 10, apicolateral view; 11, mid focus; 12, antapicolateral view. Scale bars = 5 μm .

Dimensions. Diameter (D): 16.4 (19.2) 21.5 μm , number of specimens: 39. Wall thickness (Wt): 0.9 (1.4) 1.8 μm , number of specimens: 39. Wt/D: 0.05 (0.07) 0.1. Archeopyle width: 4.4 (6.7) 8.9 μm , number of specimens: 29. Measurements obtained from specimens analyzed through transmitted light microscopy are listed in Appendix 4.B, Table 2, along with their respective England Finder (EF) coordinates. The coordinates are taken with the slide label to the right.

Comparison. *Thoracosphaera heimii* morphotype B differs from unaltered cysts of the species by the distinct calcite infill of its ornamental poroids and crystal overgrowth smoothing the appearance of surface elements. In contrast to *T. h.* morphotype A, the crystal overgrowth is more limited in *T. h.* morphotype B resulting in a thinner wall (<2 μm thick) and a wall thickness-to-diameter ratio <0.10. The latter subspecies also bears a smaller cyst diameter of <20 μm on average.

5.6 Discussion

5.6.1 K/Pg boundary position

At Site 577, multiple lines of evidence allow for constraint of the K/Pg boundary including an iridium anomaly (Michel et al., 1985), elevated concentrations of spherules (Gerstel et al., 1986), a negative carbon isotope excursion (Zachos et al., 1985, 1989) and magnetostratigraphy (Bleil,

1985; Heath et al., 1985; Monechi et al., 1985) supported by nannofossil (Monechi, 1985; Monechi et al., 1985), planktic foraminiferal (Gerstel et al., 1986) and now calcareous dinoflagellate cyst biostratigraphy (Fig. 5.2). The precise placement of the K/Pg boundary based on the nannofossil biostratigraphy of Monechi (1985) sees a mbsf depth discrepancy of 6–8 cm with Zachos et al. (1985, table 1) citing 109.19 m for their Core 12, Section 5, 128–130 cm interval sample contrary to 109.11 mbsf given for the sample at 130 cm by Monechi (1985, table 4). However, both are in agreement on 130 cm and therefore the position of Monechi (1985) at 109.11 mbsf is assumed to be identical having been essentially maintained by Monechi et al. (1985) and Wright et al. (1985) at 109.1 m. The depth correction of Dickens and Backman (2013) sees this horizon adjusted to 111.80 mbsf. Approximately 10 cm lower, at ~111.90 cm, marks the point of the shift toward elevated *Cervisiella operculata* and lower *Thoracosphaera heimii* morphotype A relative abundances in tandem with a slight increase in overall cyst concentrations (Fig. 5.2). The combination of this data presents a signal of paleoecological change that, considered together with the indications of previously discussed proxies, lends confidence in the K/Pg boundary being situated between 130 and 140 cm in Site 577 Hole 12 Core 5.

Sample No.	Max Depth (mbsf)	Total CDC Count	Total CDC Concentration (mg-1)	<i>Cervisiella operculata</i>	<i>Calciadinellum clamosum</i> subsp. <i>clamosum</i>	<i>Thoracosphaera heimii</i> morphotype A	<i>Thoracosphaera heimii</i> morphotype B	<i>Pirumella edgarii</i>	<i>Fuetererella tesserula</i>	<i>Pernambugia tuberosa</i>	<i>Calciadinellum elongatum</i>	Cyst Type A
16	110.61	209	41	33 (15.8)	117 (56)	23 (11)	24 (11.5)	1 (0.5)		1 (0.5)	1 (0.5)	9 (4.3)
15	111.21	206	286	52 (25.2)	61 (29.6)	37 (18)	45 (21.8)	3 (1.5)	3 (1.5)	3 (1.5)	2 (1)	
14	111.41	213	92	78 (36.6)	63 (29.6)	45 (21.1)	19 (8.9)		2 (0.9)	3 (1.4)	3 (1.4)	
13	111.61	208	112	75 (36.1)	47 (22.6)	34 (16.3)	47 (22.6)		3 (1.4)		2 (1)	
12	111.65	215	41	81 (37.7)	47 (21.9)	52 (24.2)	28 (13)	3 (1.4)		1 (0.5)	2 (0.9)	
11	111.69	213	101	98 (46)	27 (12.7)	41 (19.2)	33 (15.5)	3 (1.4)	4 (1.9)	5 (2.3)	2 (0.9)	
10	111.73	219	109	78 (35.6)	31 (14.6)	69 (31.5)	31 (14.2)	1 (0.5)	2 (0.9)	4 (1.8)	2 (0.9)	1 (0.5)
9	111.77	217	74	81 (37.3)	46 (21.2)	57 (26.3)	25 (11.5)	1 (0.5)	4 (1.8)	3 (1.4)		
8	111.85	215	37	93 (43.3)	37 (17.2)	49 (22.8)	24 (11.2)	1 (0.5)	2 (0.9)	3 (1.4)	3 (1.4)	3 (1.4)
7	111.89	213	12	81 (38)	60 (28.2)	48 (22.5)	13 (6.1)	8 (3.8)		2 (0.9)	1 (0.5)	
6	111.93	212	51	54 (25.5)	45 (21.2)	74 (34.9)	30 (14.2)	3 (1.4)	2 (0.9)	2 (0.9)	2 (0.9)	
5	111.97	205	26	39 (19)	65 (31.7)	75 (36.6)	17 (8.3)	6 (2.9)		2 (1)		1 (0.5)
4	111.99	206	10	42 (20.4)	65 (31.6)	56 (27.2)	32 (15.5)	4 (1.9)	1 (0.5)	2 (1)	3 (1.5)	1 (0.5)
3	112.21	206	12	39 (18.9)	75 (36.4)	57 (27.7)	28 (13.6)	2 (1)	1 (0.5)	3 (1.5)	1 (0.5)	
2	112.41	206	35	55 (26.7)	91 (44.2)	36 (17.5)	20 (9.7)	1 (0.5)	1 (0.5)	2 (1)		
1	113.02	211	490	45 (21.3)	70 (33.2)	51 (24.2)	35 (16.6)		2 (0.9)	1 (0.5)		7 (3.3)

Table 5.1. Calcareous dinoflagellate cyst (CDC) counts, concentrations and proportions (in brackets) across the K/Pg boundary interval, Site 577, Shatsky Rise. Red line denotes the position of the major assemblage shift observed herein. Dashed line denotes the K/Pg Boundary based on nannofossil biostratigraphy (Monechi, 1985) and magnetostratigraphy (Monechi et al., 1985).

5.6.2 Geo- and biochronology

The C29n/C29n boundary and the peak of the K/Pg boundary iridium anomaly have been geochemically dated at ~65.724 Ma and ~66.052 Ma respectively at sites in North America and Central Asia (e.g., Sprain et al., 2018, 2019). Given the placement of the C29n/C29n boundary at

~75 cm above the iridium peak in Site 577 Core 12 (Bleil, 1985), a numerical age scale can be interpolated which provides a framework from which to correlate the succession of bioevents. (Fig. 5.2). The caveat is the assumption of a constant sediment accumulation rate, although the associated margin for error is lessened by the narrow constraint of the interval. On the basis of this assumption, the position of the aforementioned geochronological benchmarks allow for the rate of sediment deposition to be calculated as ~2.29 m/myr (~1 cm/4.3 kyr). This estimate is consistent with the values given by Heath et al. (1985, fig. 9) based on magnetostratigraphy which see a decline from 3.5 m/myr (~1 cm/2.9 kyr) at the end of the Cretaceous to 2 m/myr (~1 cm/5 kyr) in the first 1 m above the K/Pg boundary at Site 577. This rate is more than twice of that proposed by Monechi et al. (1985) at 4.82 m/myr (~1 cm/2.1 kyr) based on lower resolution calibration of the nannofossil *Micula murus* FO and the C30r/C30n and C29r/C30n boundaries. Gerstel et al. (1986, fig. 9b) also observe a decline in sedimentation across the K/Pg boundary following the magnetostratigraphy of Bleil (1985), with their values shifting from 9.1 m/myr (1 cm/1.1 kyr) to 3 m/myr (1 cm/3.3 kyr) over the same interval. Conversely, Westerhold et al. (2008) presented astronomically calibrated high-resolution magnetostratigraphy for ODP Site 1209 which gave a rate of 1 cm/1.25 kyr immediately above the K/Pg boundary, but consideration for the bioturbation at that location was not noted. In light of our age calibration, the highest relative abundances of *Thoracosphaera heimii* morphotype A are seen to be most elevated in the last ~200 kyr of the Maastrichtian followed by those of *Cervisiella operculata* constrained to within a similar span of time in the earliest Danian prior to a return to greater levels of *Calciadinellum clamosum* which reaches dominance within 500 kyr of the K/Pg event.

Although the iridium anomaly is a classic marker for the K/Pg boundary (e.g., Molina et al., 2006), the biostratigraphic succession at Site 577 allows for more flexibility of interpretation. Monechi et al. (1985) placed the K/Pg boundary ~12 cm above the LO of the cubiform nannolith *Micula prinsii* and ~1 cm below the FO of the coccolith *Biscutum* cf. *romeinii* in her interval of elevated *Thoracosphaera* abundance. This peak ‘*Thoracosphaera*’ event was also identified at equatorial Pacific ODP Site 807 (Schmitt and Liu in Corfield et al., 1993) now herein regarded to be the *Cervisiella operculata* acme, equivalent to the calcisphere peak of Bown (2005a) at nearby ODP Site 1210. The lowermost Danian was also defined by the FOs of the coccoliths *Markalius astroporus*, *M. inversus*, *Cruciplacolithus primus* and *Cyclagelosphaera reinhardtii* as well as that of the foraminiferan *Globigerina eugubina* (Monechi, 1985; Monechi et al., 1985).

Gerstel et al. (1986) remarked that the occurrence of *G. eugubina* 16 cm below the K/Pg boundary of Monechi (1985) was atypical for the taxon which otherwise defines the basal Danian in other regions. Gerstel et al. (1986) assert that little if any sediment mixing could account for this as evidenced from the settling of spherules within 6 cm below their acme (Gerstel et al., 1986). Conversely, arguments have been mounted for the presence of bioturbation at Site 577 as to account for elevated spherule (Smit and Romein, 1985) and iridium (Kyte in Evans et al., 1995) concentrations detected over the 10 cm above their abundance peak. Gerstel et al. (1985) counter this interpretation in underscoring that no other microfossil taxa are displaced as would be expected with reworking, noting that the spherule anomaly spans over ~20 cm of the core (Fig. 5.2).

The notion that the iridium anomaly and ejecta debris are to be exclusively associated with a geologically instantaneous event (e.g., Montanari et al., 1983; Smit and Kyte, 1984) seems highly improbable given the extent of peak material dispersal throughout the Site 577 core over an interval representing >100 kyr. While an extraterrestrial bolide impact more than likely contributed to the elevated iridium and spherule concentrations (e.g., Alvarez et al., 1980; Schulte et al., 2010), the incident would have coincided with the prolonged eruption period of the Deccan Traps spanning ~800 kyr (e.g., Officer and Drake, 1985; Rocchia et al., 1990) providing a deep-mantle origin for much of the high background iridium levels. Based on the K/Pg boundary position of Monetchi (1985) and Monechi et al. (1985), the curve of the iridium anomaly is also entirely in keeping with the finding that ~75% of Deccan volcanism occurred post-Cretaceous (Sprain et al., 2019). Hull et al. (2011) applied advection-diffusion modelling to analyze the shape of the iridium anomaly in Hole 577B on the assumption that 90% of the element was deposited instantaneously with an ocean residence time of 6.3 kyr. Hull et al. (2011, p. 103) advocate for “lumpy” non-local sediment mixing (Boudreau, 1986) as an explanation to account for the iridium pulses below the acme. If both the iridium in Hole 577B and spherules in Hole 577 had shifted downward to a maximum depth of 6 cm below their acme due to bioturbation (Gerstel et al., 1986), such displacement would be in line with the estimation of Officer and Drake (1985) based on observed levels of mixing over 5 to 6 cm in deep sea sediments from modern equatorial Pacific settings (Berger and Killingley, 1982; Officer and Lynch, 1983). The potential for mixing in such a setting cannot be ruled out. However, only indirect evidence supports this interpretation at Site 577 given the absence of downward

mobilization of any characteristic Paleocene microfossils or vice versa (Gerstel et al., 1986) and the gradual, unpunctuated onset of increasing *Cervisiella operculata* abundance from samples 5 to 8.

5.6.3 Paleocology and paleoenvironmental interpretations

Evidence for phytoplankton community stability in approach to the terminal Cretaceous has been observed in the nannofossil assemblages from Shatsky Rise Site 577 (Monechi, 1985; Monechi et al., 1985) as well as from similar deep sea settings at Hess Rise Site 465 in the North Pacific and DSDP Site 527 in the eastern South Atlantic (Henriksson, 1996). Following a global trend in keeping with planktic foraminifera (e.g., Gerstel et al., 1986; MacLeod et al., 2007), the calcareous nannotaxa experience an overall decline in abundance and outright extinction of many forms at the K/Pg boundary (e.g., Streng et al., 2004b). Those that survived the K/Pg event but ultimately succumbed, did so within the following ~80 kyr (MacLeod et al., 1997). The latest Maastrichtian is also characterized by a period of general stability in the calcareous dinoflagellate cyst assemblages from other oceanic localities such as DSDP sites 356 and 357 in the western South Atlantic (Thierstein, 1981; Hildebrand-Habel et al., 1999; Hildebrand-Habel and Willems, 2000). The most characteristic change among these assemblages is elevated relative abundances of *Cervisiella operculata* beginning in the latest Maastrichtian (e.g., Thierstein, 1981; Hildebrand-Habel et al., 1999; Hildebrand-Habel and Willems, 2000; Egger et al., 2009) and peaking above the K/Pg boundary as has been observed beyond the Pacific from the U.S. Gulf Coast (Jiang and Gartner, 1986), Haiti (Keller et al., 2001), Argentina (Scasso et al., 2005; del Río et al., 2011; Guerra et al., 2021), Spain (Romein, 1977; Lamolda et al., 2005, 2016), France (Peybernés et al., 1996; Rodríguez-Tovar et al., 2010), Austria (Egger et al., 2009; Mohamed et al., 2012, 2013), Turkey (Kaya Ozer, 2014; Karabeyoğlu et al., 2019), Israel (Eshet et al., 1992), Egypt (e.g., Faris and Farouk, 2012; Kasem et al., 2017; Khozyem et al., 2019), Iraq (Kharajiany et al., 2019, 2020; Al-Qayim et al., 2020), Iran (e.g., Parandavar et al., 2013; Asgharian Rostami et al., 2018; Mahanipour et al., 2021), equatorial Atlantic (Perch-Nielsen, 1977), South Atlantic (Hildebrand-Habel et al., 1999; Hildebrand-Habel and Willems, 2000; Bernaola and Monechi, 2007), Weddell Sea (Fütterer, 1990; Hildebrand-Habel and Streng, 2003) and Indian Ocean (Ehrendorfer and Aubry, 1992; Streng et al., 2004a) demonstrating that the

shift is traceable across a variety of environmental settings, ranging from epicontinental seas to open ocean conditions. Importantly, the *C. operculata* acme is also observed at the Global Stratotype Section and Point for the base of the Danian Stage near El Kef (Jiang and Gartner, 1986; Gardin and Monechi, 1998) and neighboring Ain Settara section (Molina et al., 2009), Tunisia.

The *Cervisiella operculata* abundance acme has been interpreted as a case of species resilience in the face of ecological stress (Rodríguez-Tovar et al., 2010) and niche exploitation of largely vacated ecospace (Smit, 2005) during an interval of decreased surface productivity in the earliest Danian (Guerra et al., 2021). Zachos et al. (1985, 1989) report a significant negative $\delta^{13}\text{C}$ excursion at Site 577 (Fig. 5.2) reflective of reduced primary productivity in the ~500 kyr following the K/Pg event. This finding is consistent with carbon isotope records from deep sea cores elsewhere in both hemispheres (e.g., Zachos and Arthur, 1986; Corfield et al., 1993; Schulte et al., 2010) and the global decline in planktic microtaxa (e.g., Thierstein, 1981; MacLeod et al., 2007). A negative $\delta^{13}\text{C}$ signal can be directly associated with a reduced sedimentation rate in the early Danian (Heath, 1985) which, while attributable to a decrease in carbonate production, could also be reflective of lysocline shoaling related to ocean current changes and the northerly migration of deep-water masses (Thomas, 2004; Westerhold et al., 2008). The calcareous dinoflagellate cyst concentrations estimated from Site 577 (Fig. 5.2; Table 1) are lower than those from coeval deposits in Denmark (Wendler and Willems, 2002) and Holocene sediments from the Mediterranean (Zonneveld et al., 2001), and more similar to values obtained from modern core sediments recovered from the western equatorial Atlantic (Vink et al., 2000), as would be expected in a more oligotrophic oceanic setting distal to regions of upwelling. It would appear as though half of the calcareous dinoflagellate cyst taxa present in the Site 577 assemblages are extant species (*Calciodinellum elongatum*, *Feuttererella tesserula*, *Pernambugia tuberosa* and *Thoracosphaera heimii*) allowing for direct paleoenvironmental reconstructions based on modern ecological studies (e.g., Zonneveld et al., 2005). While *T. heimii* is a cosmopolitan species, *C. elongatum* and *P. tuberosa* are most strongly represented in assemblages from decidedly oligotrophic, oceanic locations (Vink et al., 2000; Zonneveld et al., 2000, 2001, 2005). *Feuttererella tesserula* is well documented in the fossil record ranging from the Maastrichtian to early Miocene (e.g., Hildebraiid-Habel and Willems, 2000), although comparable forms in modern sediments, assigned to *Feuttererella* cf. *tesserula*, are minor

assemblage constituents known only from isolated reports from the Mediterranean (Müller, 1972; Meier et al., 2002) and Atlantic (Vink, 2004).

A shift toward lower mean temperatures in the late Maastrichtian is widely interpreted to have preceded an abrupt phase of post-impact cooling which contributed to the end-Cretaceous extinctions over a period of up to several millennia (e.g., Galeotti et al., 2004; Vellekoop et al., 2016; Hull et al., 2020). Sea-surface temperature (SST) inferences derived from benthic foraminiferal $\delta^{18}\text{O}$ records (Zachos and Arthur, 1986; Barnet et al., 2018) and TEX₈₆ organic geochemistry (e.g., Woelders et al., 2018; Vellekoop et al., 2019) suggest that a protracted cooling phase of ~1 to 3 °C encompassed the last 50 to at least 200 kyr of the Cretaceous. Data supporting the higher end of this range were obtained from Shatsky Rise Site 577 (Zachos et al., 1985, 1989; Li and Keller, 1999), with a rise in SST estimated to have peaked at ~3 °C some 600 kyr after the K/Pg event (Zachos et al., 1989). Modern cyst culturing of *Thoracosphaera heimii* (Karwath et al., 2000) combined with field studies of the species (Zonneveld et al., 2005) has shown that its greatest numbers of cysts are produced at lower subsurface temperatures around ~16° over extended periods of time. Moreover, the most pronounced wall calcification for this taxon was also observed under the same low temperature conditions (Karwath et al., 2000). Specimens of *T. heimii* exhibit relatively stable proportions across the K/Pg boundary at Site 577 in contrast to a marked increase in the taxon in the earliest Danian at other locations such as Texas (Jiang and Gartner, 1986) and DSDP Site 366 in the Atlantic (Fütterer, 1978). However, the highest relative abundances of *T. heimii* prior to the K/Pg transition along with that for the thicker-walled *T. h.* morphotype A, are entirely consistent with an interval corresponding to the latest Maastrichtian cooling period over the last ~200 kyr of the Cretaceous as represented from samples 3–6 in the Shatsky Rise core (Fig. 5.2). Because the diagenetic crystalline overgrowth would have affected specimens from the same samples equally, their proportions in essence preserve a paleotemperature signal. Additionally, culture experiments having demonstrated a relationship between temperature and the oxygen isotope composition of *T. heimii* cysts (Zonneveld et al., 2007) presents an avenue to further refine this species as a proxy for sea-surface temperature. Conversely, Hildebrand-Habel and Streng (2003) note that *Cervisiella operculata* mass occurrence above the K/Pg boundary is constrained to mid-latitudes which implies that the species favored warm surface waters and flourished under conditions of elevated SST in the early Danian (Egger et al., 2009; Mohamed et al., 2012). *Cervisiella operculata*

elevation is also not abrupt at Site 577 and may actually be occurring in Sample 6 due to the onset of a warming shift in the closing millennia of the Cretaceous (Fig. 5.2). At higher latitudes, the post-Cretaceous *C. operculata* peak is delayed, as seen at ODP Site 690 in the Weddell Sea, represented by lower relative abundances (Pospichal and Wise Jr., 1990) suggesting a slow graduation of warmer surface waters to southern high latitudes in the ~300 kyr that followed the K/Pg event.

5.7 Conclusion

Calcareous dinoflagellate cysts are an understudied component of the marine fossil record representing a small but significant group of phytoplankton present in the oceans since the Triassic Period (Jafar, 1979). Among the calcareous biogenic constituents of marine sediments, they are often neglected in paleontological research in favor of nannofossils and the tests of foraminifera. However, the ease of recoverability and sheer abundance of calcareous dinoflagellate cysts at DSDP Site 577 on Shatsky Rise has offered an excellent opportunity to analyze these assemblages. This study has been the first to demonstrate the utility of these taxa for both biostratigraphy and paleoenvironmental reconstructions across the K/Pg boundary interval at a deep sea setting from an undisturbed depositional sequence in the Pacific Ocean. In the virtual absence of organic-walled dinoflagellate cysts, we recognize the presence of eight calcareous species—four of which exist today—allowing for direct correlation with known environmental preferences of modern taxa as to ascertain a definitive oligotrophic association. Presented in a synthesis with previous findings from geochemical data and chronostratigraphic controls, we interpret two major signals within the studied assemblages of the Site 577 core. Sequentially, the first corresponds to an interval of elevated relative abundance for thick-walled specimens of *Thoracosphaera heimii* (morphotype A) in concert with the late Maastrichtian decrease in global mean temperature. The second signal occurring at the K/Pg boundary transition is that of the *Cervisiella operculata* acme, observed from numerous locations elsewhere in both hemispheres, coinciding with the onset of warming conditions in the earliest Danian. While the terminal Cretaceous event did not precipitate the extinction of any calcareous dinoflagellate cyst species at Shatsky Rise, the results of this investigation illustrate that its

effects and associated climatic shifts nevertheless had a measurable and long-lasting impact on the phytoplankton community in the equatorial Pacific.

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Chapter 6

Conclusions

6.1 Summary of research

Dinoflagellate cysts offer tremendous potential as environmentally sensitive indicators reflecting trends of nutrient influx and associated primary productivity along with chemical and temperature changes in marine settings (e.g., Dale, 1996; Popescue et al., 2009; Mertens et al., 2011). Their morphological characters can reflect a range of responses to specific environmental factors and stressors adding a valuable dimension to their potential for paleontological application. This research has aimed to serve as a foothold for marine palynology in the North Pacific, establishing a biostratigraphic framework from which further work can proceed to reconstruct paleoenvironmental conditions within the established context for the Late Cretaceous–early Paleogene. Using dinoflagellate cysts as principal tools of investigation, the absence of age-diagnostic taxa in the uppermost Cretaceous sandstones elsewhere in the Vancouver Island region highlights the crucial importance of the fine-grained sedimentary rocks of the Oyster Bay Formation in establishing the position of the K/Pg boundary in relation to the uppermost Cretaceous of the Nanaimo Group succession and the paleoecological responses within the phytoplankton record.

Chapter 1 presented a significant contribution in the discovery of the first K/Pg boundary west of the Rocky Mountains on eastern Vancouver Island based on high-resolution dinoflagellate cyst biostratigraphy. The chapter also reconstructed a coastal to estuarine paleoenvironment throughout the upper Maastrichtian–lower Selandian interval based on dinoflagellate cysts supported by geochemical data. The results demonstrate shifts in assemblage composition among several major constituent dinoflagellate cyst ecogroups along with the first consistent occurrences (FCOs) and last consistent occurrences (LCOs) of K/Pg boundary indicator taxa (e.g., LCO of *Palynodinium grallator*; FCO of *Danea californica*). These observations are consistent with the same bioevents observed at the Global Stratotype Section and Point for the basal Danian at El Kef, Tunisia and the majority of other studied locations

across the same time interval (see discussion under section 2.7 and lists of published reports in Appendix 1.C). The work also established five distinct dinoflagellate cyst biozones spanning the ~4.5 to 5 myr interval following statistical computation through cluster analysis of assemblage variance as well as the positions of index taxon first occurrence (FO) and last occurrence (LO) datums. This study also provided a comprehensive review of the published peer-reviewed literature and global data synthesis of known records of key dinoflagellate cyst index taxa of the Oyster Bay Formation. In doing so, it identified the approximate placement of both the K/Pg and Danian/Selandian boundaries. The paleoenvironmental interpretations and examination of possible factors impacting primary productivity reached beyond those of the immediate local setting and considered broader climatic signals and Earth system changes relating to the end-Cretaceous event. Marine regressions and transgressions were inferred across the K/Pg interval based on dinoflagellate cyst assemblage fluctuations, terrestrial palynology and sequence stratigraphy. The marine assemblages were also compared to those of neighboring coeval biotic provinces leading to inferences of evolving ocean circulation patterns and transitions between paleotemperature regimes from Late Cretaceous to early Paleogene time.

Chapters 2 and 3 are a testament to taxonomy as the foundation of a sound, consistent approach to the interpretation of the dinoflagellate cyst fossil record. As a case study revising the genus *Cannosphaeropsis* from material recovered from the Oyster Bay Formation, Chapter 2 provides a systematic description and conceptual discussion to emphasize what insights specific characters can reveal about species paleoecology and paleoenvironmental adaptation based on the presentation of similar features in modern analogue taxa (see discussion section 3.7). The study uses extensive light-transmitted microscopy and SEM analysis to describe a series of new subspecies spanning an unprecedented plexus of morphology in the spiniferate species *Cannosphaeropsis franciscana*. The findings of the investigation carry implications for interpreting gonyaulacacean morphology from the standpoint of ecophenotypic expression as represented by variance in cyst wall vesiculation, process types and autophragm geometry, recorded in response to changing environmental conditions across the K/Pg interval. With consideration of abundance trends in members of the genus *Hafniasphaera*, the case is made that vesiculation among spiniferate gonyaulacaceans may be an adaptation to sustain buoyancy in the water column under increasingly stratified conditions. Furthermore, a comprehensive synthesis of the published peer-reviewed records of species belonging to *Cannosphaeropsis* sees the genus

as a representative of highly specialized dinoflagellate cysts with a coastal to oceanic preference often found in deposits associated with transgressive regimes.

Chapter 3 recognizes a new protoperidiniacean dinoflagellate cyst in *Phelodinium fensomei* sp. nov. with potential as a biostratigraphic marker due to its constraint within strata of Danian age in the Appian Way section of the Oyster Bay Formation. The SEM techniques employed also reveal features of surface ornamentation not previously observed within the protoperidiniacean group and epifluorescence analysis provided paleoecological insights for the species lending evidence to a strictly heterotrophic mode of life.

Chapter 4 consists of the first detailed study of the calcareous dinoflagellate cyst fossil record in the North Pacific with a focus on the assemblages crossing the K/Pg boundary interval as revealed through a succession of samples obtained from the hydraulic piston core of Deep Sea Drilling Program Site 577 on Shatsky Rise. This investigation benefited greatly from the data which previously established a robust chemo-, magneto- and nannofossil/foraminiferal biostratigraphic framework (see: Bleil, 1985; Michel et al., 1985; Monechi, 1985; Monechi et al., 1985; Zachos et al., 1985; Gerstel et al., 1986) enabling well constrained time calibration throughout an undisturbed sequence of calcareous ooze. The calcareous dinoflagellate cysts were limited to eight species-level taxa. Two major bioevents were found to have occurred, the first being the predominance of thick-walled *Thoracosphaera heimii* morphotype A in the latest Maastrichtian and the second being the globally recognized interval of *Cervisiella operculata* peak abundance in the early Danian. The signals of these assemblage constituents are interpreted to reflect end-Cretaceous cooling and early Paleocene warming in the context of geochemical sea-surface temperature proxies at the same location (e.g., Zachos et al., 1989; Li and Keller, 1999) and in other regions (e.g., Barnet et al., 2018; Woelders et al., 2018). Changes impacting K/Pg paleoproductivity and evidence of taxon niche exploitation were also found to be reflected by *C. operculata* cyst abundance. Test morphology in *T. heimii* was seen to be more indicative of temperature fluctuation.

6.2 Comparison of Vancouver Island and DSDP Site 577 cyst records

Following the body of work conducted on the Oyster Bay Formation of Vancouver Island after previous investigation of uppermost Nanaimo Group strata, examination of the Shatsky Rise core proceeded with the intent to capture a broad measure of the impact of the terminal Cretaceous event within this central component of the phytoplankton community in the North Pacific. The combination of these studies has presented a unique opportunity to contrast the coeval dinoflagellate cyst fossil records from two sites across the world's largest ocean, those of the Oyster Bay Formation on Vancouver Island in the northeast Pacific and the DSDP Site 577 core from Shatsky Rise in the northwest Pacific. Geographically, both locations were likely separated by >8,000 km at ~66 Ma much as they are today, but the difference in paleoenvironmental settings provides the starkest contrast as is evidenced by the assemblage composition shifts in phytoplankton responsivity to the K/Pg event. Diverse organic-walled dinoflagellate cyst assemblages in excess of 100 species represented in the Oyster Bay Formation indicated a highly productive coastal to estuarine setting near the modern North American margin presumably in association with nutrient-rich waters fed by a combination of upwelling and terrigenous outflow. The near absence of organic-walled dinoflagellate cysts in the Shatsky Rise deposits and strong representation of a small number of calcareous cyst taxa are the hallmarks of a pelagic, oligotrophic environment in a lower bathyal setting. At both sites, the presence of extant taxa in the fossil record (e.g., members of the *Spiniferites* group within the Oyster Bay Formation; half of the species in the studied interval of the Shatsky Rise Site 577 core) allows for direct paleoenvironmental inferences based on the confirmed habitat, conditional and latitudinal preferences of modern species in the upper water column. By extension, a synthesis of the global literature on dinoflagellate cyst K/Pg indicator taxa has enabled the correlation of extinct species with episodes of climatic change in similar depositional environments preceding and following the terminal Cretaceous event. The scope of one of the greatest cataclysmic events in Earth history is shown to have had complex and long-lasting effects on this specialized and tenacious component of the marine environment. These findings serve to bolster the global dataset with new insights from a vast and understudied region in concert with the integration of data from a host of other paleoenvironmental proxies and geochemical tools employed by researchers at hundreds of locations across both hemispheres.

6.3 Future work

The investigations undertaken in this thesis have demonstrated that dinoflagellate cyst assemblages serve to elevate understanding of past climatic fluctuations, paleobiogeography and the evolution of ocean basins during Late Cretaceous–early Paleogene time. Additionally, the presence of cosmopolitan index taxa in the North Pacific, along with associated phytoplankton bioevents and shifts in cyst abundance, enables direct paleoenvironmental and paleoecological comparison with well-studied sections in similar settings from around the world. This research forms the basis for a refined biostratigraphic framework for the pre-Quaternary of the North Pacific. Future work can draw on the global dinoflagellate cyst dataset utilizing this microfossil group as a major asset in approach to resolving questions of North Pacific biotic endemism, paleoecology, paleoproductivity and the tectonic history of the region. The taxonomic work herein presents new insights toward the reinterpretation of morphospecies as ecophenotypes, furthering the strength of specialized species as nuanced paleoenvironmental indicators. With the dinoflagellate cyst fossil record extending into the Triassic, a vast expanse of deep time remains unexplored in the North Pacific realm. Interregional variance in the phytoplankton response to other large-scale Earth system changes affecting the oceans in the more recent past could be examined such as Cretaceous anoxic events (e.g., Dodsworth, 2000, 2004; Pearce et al., 2009) and the Paleocene–Eocene Thermal Maximum (e.g., Bujak and Brinkhuis, 1998; Shcherbinina et al., 2016; Frieling and Sluijs, 2018), which have been extensively studied elsewhere but remain unaddressed in this part of the world. To a broader extent, these studies add resolution to the evolution of a major component of the ocean food web with modern economic implications for resource exploration and use as markers of marine ecosystem stresses relating to climate change.

References

- Açikalin, S., Vellekoop, J., Ocakoğlu, F., Ömer Yilmaz, I., Smit, J., Altiner, S.T., Goderis, S., Vonhof, H., Speijer, R.P., Woelders, L., Fornaciari, E., Brinkhuis, H., 2015. Geochemical and palaeontological characterization of a new K-Pg boundary locality from the northern branch of the Neo-Tethys: Mudurnu - Göynük Basin, NW Turkey. *Cretaceous Research* 52, 251–267.
- Al-Qayim, B.A., Kharajany, S.O.A., Wise Jr., S.W., 2020. Biostratigraphic analysis of the K/Pg boundary using calcareous nannofossils from the Sulaimani area, Kurdistan Region, Iraq. *Kuwait Journal of Science* 47, 92–105.
- Alberti, G., 1959. Zur Kenntnis der Gattung *Deflandrea* Eisenack (Dinoflag.) in der Kreide und im Alttertiär Nord- und Mitteldeutschlands. *Mitteilungen aus dem Geologischen Staatsinstitut in Hamburg* 28, 93–105, pls 8–9 (in German).
- Alberti, G., 1961. Zur Kenntnis mesozoischer und alttertiärer Dinoflagellaten und Hystrichosphaerideen von Nord- und Mitteldeutschland sowie einigen anderen europäischen Gebieten. *Palaeontographica, Abteilung A*, 116, 1–58, pls. 1–12 (in German).
- Alegret, L., Thomas, E., 2009. Food supply to the seafloor in the Pacific Ocean after the Cretaceous/Paleogene boundary event. *Marine Micropaleontology* 73, 105–116.
- Alegret, L., Thomas, E., Lohmann, K.C., 2012. End-Cretaceous marine mass extinction not caused by productivity collapse. *Proceedings of the National Academy of Sciences* 109, 728–732.
- Allameh, M., Torshizian, H., Habiballahei, N., 2011. Palynology and paleoecology of the Sarcheshmeh Formation in Daddanlou village, southeast Qouchan (Khorasan Razavi). *Sedimentary Facies* 4, 64–76.
- Alsenz, H., Regnery, J., Ashckenazi-Polivoda, S., Meilijson, A., Ron-Yankovich, L., Abramovich, S., Illner, P., Almogi-Labin, A., Feinstein, S., Berner, Z., Püttmann, W., 2013. Sea surface temperature record of a Late Cretaceous tropical Southern Tethys upwelling system. *Palaeogeography, Palaeoclimatology, Palaeoecology* 392, 350–358.
- Alvarez, L.W., Alvarez, W., Asaro, F., Michel, H.V., 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science* 208, 1095–1108.
- Antolinez-Delgado, H., Oboh-Ikuenobe, F.E., 2007. New species of dinoflagellate cysts from the Paleocene of the Anambra Basin, southeast Nigeria. *Palynology* 31, 53–62.
- Archibald, J.D., Clemens, W.A., Padian, K., Rowe, T., Macleod, N., Barrett, P.M., Gale, A., Holroyd, P., Dieter-Sues, H., Arens, N.C., Horner, J.R., Wilson, G.P., Goodwin, M.B.,

- Brochu, C.A., Lofgren, D.L., Hurlbert, S.H., Hartman, J.H., Eberth, D.A., Wignall, P.B., Currie, P.J., Weil, A., Prasad, G.V.R., Dingus, L., Courtillot, V., Milner, A., Milner, A., Bajpai, S., Ward, D.J., Sahni, A., 2010. Cretaceous extinctions: Multiple causes. *Science* 328, 973.
- Artzner, D.G., Dörhöfer, G., 1978. Taxonomic note: *Lejeunecysta* nom. nov. pro. *Lejeunia* Gerlach 1961 emend. Lentin and Williams 1976—dinoflagellate cyst genus. *Canadian Journal of Botany* 56, 1381–1382.
- Asgharian Rostami, M., Leckie, R.M., Font, E., Frontalini, F., Finkelstein, D., Koeberl, C., 2018. The Cretaceous-Paleogene transition at Galanderud (northern Alborz, Iran): A multidisciplinary approach. *Palaeogeography, Palaeoclimatology, Palaeoecology* 493, 82–101.
- Askin, R.A., 1988. Campanian to Paleocene palynological succession of Seymour and adjacent islands, northeastern Antarctic Peninsula. *Geological Society of America, Memoir* 169, 131–153.
- Askin, R.A., Jacobson, S.R., 1996. Palynological change across the Cretaceous-Tertiary boundary on Seymour Island, Antarctica: environmental and depositional factors. In: Macleod, N., Keller, G. (Eds.), *Cretaceous-Tertiary mass extinctions: biotic and environmental changes*. W.W. Norton & Co., New York, pp. 7–25.
- Atkinson, B.A., Stockey, R.A., Rothwell, G.W., Mindell, R.A., Bolton, M.J., 2015. Lauraceous flowers from the Eocene of Vancouver Island: *Tinaflora beardia* gen. et sp. nov. (Lauraceae). *International Journal of Plant Sciences* 176, 567–585.
- Awad, W.K., Oboh-Ikuenobe, F.E., 2016. Early Paleogene dinoflagellate cysts from ODP Hole 959D, Côte d'Ivoire-Ghana Transform Margin, West Africa: New species, biostratigraphy and paleoenvironmental implications. *Journal of African Earth Sciences* 123, 123–144.
- Aydin, T., 2013. Dinoflagellate cyst biostratigraphy, palynofacies and paleoenvironmental analysis of the Maastrichtian and basal Danian, Brazos River, Texas (unpubl. MSc. thesis). Texas A&M University, College Station, Texas, 121 pp.
- Backhouse, J., 2006. Albian (Lower Cretaceous) dinoflagellate cyst biostratigraphy of the Lower Gearle Siltstone, southern Carnarvon Basin, Western Australia. *Palynology* 30, 43–68.
- Bain, H.A., Hubbard, S.M., 2016. Stratigraphic evolution of a long-lived submarine channel system in the Late Cretaceous Nanaimo Group, British Columbia, Canada. *Sedimentary Geology* 337, 113–132.
- Balduzzi, A., Msaky, E., Trincianti, E., Manum, S.B., 1992. Mesozoic Karoo and post-Karoo formations in the Kilwa area, southeastern Tanzania—a stratigraphic study based on palynology, micropaleontology and well log data from the Kizimbani well. *Journal of African Earth Sciences* 15, 405–427.

- Barke, J., van der Burgh, J., van Konijnenburg-van Cittert, J.H.A., Collinson, M.E., Pearce, M.A., Bujak, J., Heilmann-Clausen, C., Speelman, E.N., van Kempen, M.M.L., Reichart, G.-J., Lotter, A.F., Brinkhuis, H., 2012. Coeval Eocene blooms of the freshwater fern *Azolla* in and around Arctic and Nordic seas. *Palaeogeography, Palaeoclimatology, Palaeoecology* 337–338, 108–119.
- Barnard, A.S., Russo, S.P., 2009. Modelling nanoscale FeS₂ formation in sulfur rich conditions. *Journal of Materials Chemistry* 19, 3389–3394.
- Barnet, J.S.K., Littler, K., Kroon, D., Leng, M.J., Westerhold, T., Röhl, U., Zachos, J.C., 2018. A new high-resolution chronology for the late Maastrichtian warming event: Establishing robust temporal links with the onset of Deccan volcanism. *Geology* 46, 147–150.
- Batten, D.J., 1996. Palynofacies and paleoenvironmental interpretation. In: Jansonius, J., McGregor, D.C. (Eds.), *Palynology: principles and applications*, volume 3. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 1011–1064.
- Beiranvand, B., Zaghib-Turki, D., Ghasemi-Nejad, E., 2014. Integrated biostratigraphy based on planktonic foraminifera and dinoflagellates across the Cretaceous/Paleogene (K/Pg) transition at the Izeh section (SW Iran). *Comptes Rendus Palevol* 13, 235–258.
- Bell, D.G., Bjorøy, M., Grogan, P., Kilenyi, T., Trayner, P., 1990. Better prospect evaluation with organic geochemistry, biostratigraphy and seismics. *Oilfield Review* 2, 24–42.
- Below, R., 1987. Evolution und Systematik von Dinoflagellaten-Zysten aus der Ordnung Peridinales. I. Allgemeine Grundlagen und Subfamilie Rhaetogonyaulacoideae (Familie Peridiniaceae). *Palaeontographica, Abteilung B* 205, 1–164, pl. 1–26 (in German).
- Benninghoff, W.S., 1962. Calculation of pollen and spores density in sediments by addition of exotic pollen in known quantities. *Pollen et Spores* 332–333.
- Berger, W.H., Killingley, J.S., 1982. Box cores from the equatorial Pacific: ¹⁴C sedimentation rates and benthic mixing. *Marine Geology* 45, 93–125.
- Bernaola, G., Monechi, S., 2007. Calcareous nannofossil extinction and survivorship across the Cretaceous–Paleogene boundary at Walvis Ridge (ODP Hole 1262C, South Atlantic Ocean). *Palaeogeography, Palaeoclimatology, Palaeoecology* 255, 132–156.
- Besems, R.E., 1993. Dinoflagellate cyst biostratigraphy of Tertiary and Quaternary deposits of offshore NW Borneo. *Geological Society of Malaysia, Bulletin* 33, 65–93.
- Bercovici, A., Vellekoop, J., 2017. Methods in paleopalynology and palynostratigraphy: An application to the K-Pg boundary. In: Zeiger, K.E., Parker, W. (Eds.), *Terrestrial depositional systems: Deciphering complexities through multiple stratigraphic methods*. Elsevier, Amsterdam, pp. 127–164.

- Bercovici, A., Pearson, D., Nichols, D., Wood, J., 2009. Biostratigraphy of selected K/T boundary sections in southwestern North Dakota, USA: toward a refinement of palynological identification criteria. *Cretaceous Research* 30, 632–658.
- Berner, R.A., 1984. Sedimentary pyrite formation: An update. *Geochimica et Cosmochimica Acta* 48, 605–615.
- Bhattacharya, J.P., 1994. Cretaceous Dunvegan Formation of the Western Canada Sedimentary Basin, in: Mossop, G.D., Shetsen, I. (Eds.), *Geological Atlas of the Western Canada Sedimentary Basin*. Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, pp. 365–373.
- Bijl, P., Guerstein, G., Sanmiguel, J.E., Sluijs, A., Casadio, S., Valencia, V., Amenábar, C., Encinas, A., 2021. Campanian–Eocene dinoflagellate cyst biostratigraphy in the southern Andean foreland basin: Implications for Drake Passage throughflow. *Andean Geology* 48, 185–218.
- Bird, M.I., Brunskill, G.J., Chivas, A.R., 1995. Carbon-isotope composition of sediments from the Gulf of Papua. *Geo-Marine Letters* 15, 153–159.
- Bleil, U., 1985. The magnetostratigraphy of northwest Pacific sediments, Deep Sea Drilling Project Leg 86. Deep Sea Drilling Project, Initial Reports 86, 441–458.
- Bogus, K., Harding, I.C., King, A., Charles, A.J., Zonneveld, K.A.F., Versteegh, G.J.M., 2012. The composition and diversity of dinosporin in species of the *Apectodinium* complex (Dinoflagellata). *Review of Palaeobotany and Palynology* 183, 21–31.
- Bogus, K., Mertens, K.N., Lauwaert, J., Harding, I.C., Vrielinck, H., Zonneveld, K.A.F., Versteegh, G.J.M., 2014. Differences in the chemical composition of organic-walled dinoflagellate resting cysts from phototrophic and heterotrophic dinoflagellates. *Journal of Phycology* 50, 254–266.
- Boltenhagen, E., 1977. Microplankton du Crétacé Supérieur du Gabon. *Cahiers de Paléontologie* 1–151, pls. 1–25.
- Boudreau, B.P., 1986. Mathematics of tracer mixing in sediments: II. Nonlocal mixing and biological conveyor-belt phenomena. *American Journal of Science* 286, 199–238.
- Bowman, V.C., Francis, J.E., Riding, J.B., 2013. Late Cretaceous winter sea ice in Antarctica? *Geology* 41, 1227–1230.
- Bowman, V.C., Francis, J.E., Riding, J.B., Hunter, S.J., Haywood, A.M., 2012. A latest Cretaceous to earliest Paleogene dinoflagellate cyst zonation from Antarctica, and implications for phytoprovincialism in the high southern latitudes. *Review of Palaeobotany and Palynology* 171, 40–56.

- Bowman, V., Ineson, J., Riding, J., Crame, J., Francis, J., Condon, D., Whittle, R., Ferraccioli, F., 2016. The Paleocene of Antarctica: Dinoflagellate cyst biostratigraphy, chronostratigraphy and implications for the palaeo-Pacific margin of Gondwana. *Gondwana Research* 38, 132–148.
- Bown, P.R., 2005a. Selective calcareous nannoplankton survivorship at the Cretaceous-Tertiary boundary. *Geology* 33, 653–656.
- Bown, P.R., 2005b. Cenozoic calcareous nannofossil biostratigraphy, ODP Leg 198 Site 1208 (Shatsky Rise, northwest Pacific Ocean). In: Bralower, T.J., Premoli Silva, I., Malone, M.J. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results 198*, College Station, Texas, pp. 1–44.
- Bralower, T.J., Premoli Silva, I., Malone, M.J., 2002. New evidence for abrupt climate change in the Cretaceous and Paleogene: An Ocean Drilling Program expedition to Shatsky Rise, northwest Pacific. *GSA Today* 12, 4–10.
- Bramlette, M.N., Riedel, W.R., 1954. Stratigraphic value of discoasters and some other microfossils related to Recent Coccolithophores. *Journal of Paleontology* 28, 385–403.
- Bramlette, M.N., Martini, E., 1964. The great change in calcareous nannoplankton fossils between the Maestrichtian and Danian. *Micropaleontology* 10, 291–322.
- Braman, D.R., 2013. Triprojectate pollen occurrence in the Western Canada Sedimentary Basin and the group's global relationships. *Royal Tyrrell Museum of Palaeontology Contribution Series* 1, 538 pp.
- Braman, D.R., 2018. Terrestrial palynostratigraphy of the Upper Cretaceous (Santonian) to lowermost Paleocene of southern Alberta, Canada. *Palynology* 42, 102–147.
- Braman, D.R., Sweet, A.R., 2012. Biostratigraphically useful Late Cretaceous–Paleocene terrestrial palynomorphs from the Canadian Western Interior Sedimentary Basin. *Palynology* 36, 8–35.
- Brenner, W.W., Biebow, N., 2001. Missing autofluorescence of recent and fossil dinoflagellate cysts—an indicator of heterotrophy? *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 219, 229–240.
- Brinkhuis, H., 1994. Late Eocene to early Oligocene dinoflagellate cysts from the Priabonian type-area (northeast Italy): biostratigraphy and paleoenvironmental interpretation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 107, 121–163.
- Brinkhuis, H., Biffi, U., 1993. Dinoflagellate cyst stratigraphy of the Eocene/Oligocene transition in central Italy. *Marine Micropaleontology* 22, 131–183.

- Brinkhuis, H., Leereveld, H., 1988. Dinoflagellate cysts from the Cretaceous/Tertiary boundary sequence of El Kef, northwest Tunisia. *Review of Palaeobotany and Palynology* 56, 5–19.
- Brinkhuis, H., Schiøler, P., 1996. Palynology of the Geulhemmerberg Cretaceous/Tertiary boundary section (Limburg, SE Netherlands). *Geologie En Mijnbouw*, 75, 193–213.
- Brinkhuis, H., Zachariasse, W.-J., 1988. Dinoflagellate cysts, sea level changes and planktonic foraminifers across the Cretaceous–Tertiary boundary at El Haria, northwest Tunisia. *Marine Micropaleontology* 13, 153–191.
- Brinkhuis, H., Powell, A.J., Zevenboom, D., 1992. High-resolution dinoflagellate cyst stratigraphy of the Oligocene/Miocene transition interval in north-west and central Italy. In: Head, M.J, Wrenn, J.H. (Eds.), *Neogene and Quaternary dinoflagellate cysts and acritarchs*. American Association of Stratigraphic Palynologists Foundation, Dallas, pp. 219–258.
- Brinkhuis, H., Romein, A.J.T., Smit, J., Zachariasse, J.-W., 1994. Danian–Selandian dinoflagellate cysts from lower latitudes with special reference to the El Kef section, NW Tunisia. *GFF* 116, 46–48.
- Brinkhuis, H., Bujak, J.P., Smit, J., Versteegh, G.J.M., Visscher, H., 1998. Dinoflagellate-based sea surface temperature reconstructions across the Cretaceous–Tertiary boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology* 141, 67–83.
- Brown, S., Downie, C., 1985. Dinoflagellate cyst stratigraphy of Paleocene to Miocene sediments from the Goban Spur (Sites 548–550, Leg 80). *Deep Sea Drilling Project, Initial Reports* 80, 643–651.
- Bubík, M., Adamová, M., Bák, M., Franců, J., Gedl, P., Mikuláš, R., Švábenická, L., Uchman, A., 2002. Results of the investigations at the Cretaceous/Tertiary boundary in the Magura Flysch near Uzgrůň. *Geologické výzkumy na Moravě a ve Slezsku* 10, 18–22 (in Czech).
- Buczkowski, E.L., Stockey, R.A., Atkinson, B.A., Rothwell, G.W., 2016. *Cunninghamia beardii* sp. nov. (Cupressaceae: Cunninghamioideae), anatomically preserved pollen cones from the Eocene of Vancouver Island, British Columbia, Canada. *International Journal of Plant Sciences* 177, 103–114.
- Bujak, J.P., Davies, E.H., 1983. Modern and fossil Peridiniineae. *American Association of Stratigraphic Palynologists, Contribution Series* 13, 202 pp.
- Bujak, J.P., Downie, C., Eaton, G.L., Williams, G.L., 1980. Dinoflagellate cysts and acritarchs from the Eocene of southern England. *Special Papers in Palaeontology* 24, 100 pp.
- Bütschli, O., 1885. Erster Band. Protozoa. In: Bronns, H.G. (Ed.), *Die Klassen und Ordnungen des Thier-Reichs, wissenschaftlich dargestellt in Wort und Bild*. C. F. Winter'sche Verlagsbuchhandlung, Leipzig and Heidelberg, pp. 865–1088 (in German).

- Cao, Wenchao, Zahirovic, S., Flament, N., Williams, S., Golonka, J., Müller, R.D., 2017. Improving global paleogeography since the late Paleozoic using paleobiology. *Biogeosciences* 14, 5425–5439.
- Carter, E., Haggart, J., 2006. Radiolarian biogeography of the Pacific region indicates a mid-to high-latitude (> 30) position for the Insular superterrane since the late Early Jurassic. In: Haggart, J.W, Enkin, R.J., Monger, J.W.H. (Eds.), *Paleogeography of the North American Cordillera: evidence for and against large-scale displacements*. Geological Association of Canada, Special Paper, 46, pp. 109–132.
- Cathyl-Bickford, C.G., Hoffman, G.L., 1998. Geology of the Quinsam River area, Comox coalfield, British Columbia NTS 92F/14; 92K/3. British Columbia Ministry of Energy and Mines, Geological Survey Branch, Open File 1998-07.
- Cerling, T.E., Hart, J.A., Hart, T.B., 2004. Stable isotope ecology in the Ituri Forest. *Oecologia* 138, 5–12.
- Chakir, S., Slimani, H., Hssaida, T., Kocsis, L., Gheerbrant, E., Bardet, N., Jalil, N.-E., Mouflih, M., Mahboub, I., Jbari, H., 2020. Dinoflagellate cyst evidence for the age, palaeoenvironment and paleoclimate of a new Cretaceous–Paleogene (K/Pg) boundary section at the Bou Angueur syncline, Middle Atlas, Morocco. *Cretaceous Research* 106, 104219.
- Chalapathi Rao, N.V., Lehmann, B., Balaram, V., 2014. Platinum-group element (PGE) geochemistry of Deccan orangeites, Bastar craton, central India: Implication for a non-terrestrial origin for iridium enrichment at the K–Pg boundary. *Journal of Asian Earth Sciences* 84, 24–33.
- Châteauneuf, J.-J., 1980. Palynostratigraphie et paléoclimatologie de l'Eocène Supérieur et de l'Oligocène du Bassin de Paris. *Bulletin Bureau de Recherches Géologiques et Minières, Mémoires* 116, 1–360 (in French).
- Chmura, C.A., 1973. Upper Cretaceous (Campanian–Maestrichtian) angiosperm pollen from the western San Joaquin Valley, California. *Palaeontographica, Abteilung B* 141, 89–171.
- Claeys, P., Kiessling, W., Alvarez, W., 2002. Distribution of Chicxulub ejecta at the Cretaceous–Tertiary boundary. *Geological Society of America, Special Papers* 356, 55–68.
- Clemmensen, A., Thomsen, E., 2005. Palaeoenvironmental changes across the Danian–Selandian boundary in the North Sea Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology* 219, 351–394.
- Coates, J.A., 1974. Geology of the Manning Park area, British Columbia. *Geological Survey of Canada, Bulletin* 238, 1–177.
- Cockburn, T., Haggart, J.W., 2007. A preliminary report on the marine fauna of the Eocene

- Appian Way site. Seventh British Columbia paleontological symposium, program and abstracts. British Columbia Paleontological Alliance, May 18–21, Courtenay, British Columbia, 23.
- Cohen, C.L.D., 1965. Coccoliths and discoasters from Adriatic bottom sediments. *Leidse Geologische Mededelingen* 35, 1–44, pls. 1–25.
- Cohen, K.M., Harper, D.A.T., Gibbard, P.L., Junxuan Fan, 2013. The ICS international chronostratigraphic chart. *Episodes* 36, 199–204.
- Cookenboo, H.O., Bustin, R.M., 1988. Jura-Cretaceous (Oxfordian to Cenomanian) stratigraphy of the north-central Bowser Basin, northern British Columbia. *Canadian Journal of Earth Sciences* 26, 1001–1012.
- Cookson, I.C., Eisenack, A., 1958. Microplankton from Australian and New Guinea upper Mesozoic sediments. *Proceedings of the Royal Society of Victoria* 70, 19–78, pls. 1–12.
- Cookson, I.C., Eisenack, A., 1960. Microplankton from Australian Cretaceous sediments. *Micropaleontology* 6, 1–18.
- Cookson, I.C., Eisenack, A., 1962. Additional Microplankton from Australian Cretaceous Sediments. *Micropaleontology* 8, 485–507.
- Cookson, I.C., Eisenack, A., 1965. Microplankton from the Paleocene Pebble Point Formation, south-western Victoria. *Proceedings of the Royal Society of Victoria* 79, 139–146, pls 18–19.
- Cookson, I.C., Eisenack, A., 1974. Mikroplankton aus australischen Mesozoischen und Tertiären sedimenten. *Palaeontographica, Abteilung B* 148, 44–93, pls. 20–29 (in German).
- Corfield, R.M., Sliter, W.V., Premoli Silva, I., Tarduno, J.A., Schmitt, R.A., Liu, Y.-G., Wise Jr., S.W., Mao, S., Cartlidge, J.E., Berger, W.H., 1993. Synthesis of Cretaceous/Tertiary boundary studies at Hole 807C. In: Berger, W.H., Kroenke, L.W., Mayer, L.A. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, Texas, pp. 745–751.
- Corradini, D., 1973. Non-calcareous microplankton from the Upper Cretaceous of the northern Apennines. *Bollettino della Società Paleontologica Italiana* 11, 119–197, pls. 19–39.
- Costa, L.I., Downie, C., 1979. Cenozoic dinocyst stratigraphy of sites 403 to 406 (Rockall Plateau) IPOD, Leg 48. Deep Sea Drilling Project, Initial Reports 48, 513–529.
- Coutts, D.S., Matthews, W.A., Englert, R.G., Brooks, M.D., Boivin, M.-P., Hubbard, S.M., 2020. Along-strike variations in sediment provenance within the Nanaimo Basin reveal mechanisms of forearc basin sediment influx events. *Lithosphere* 12, 180–197.

- Crickmay, C.H., Pocock, S.A.J., 1963. Cretaceous of Vancouver, British Columbia, Canada. American Association of Petroleum Geologists, Bulletin 47, 1928–1942.
- Crouch, E.M., Brinkhuis, H., 2005. Environmental change across the Paleocene-Eocene transition from eastern New Zealand: A marine palynological approach. *Marine Micropaleontology* 56, 138–160.
- Crouch, E.M., Mildenhall, D.C., Neil, H.L., 2010. Distribution of organic-walled marine and terrestrial palynomorphs in surface sediments, offshore eastern New Zealand. *Marine Geology* 270, 235–256.
- Crouch, E.M., Willumsen, P.S., Kulhanek, D.K., Gibbs, S.J., 2014. A revised Paleocene (Teurian) dinoflagellate cyst zonation from eastern New Zealand. *Review of Palaeobotany and Palynology* 202, 47–79.
- Culver, S.J., 2003. Benthic foraminifera across the Cretaceous–Tertiary (K–T) boundary: A review. *Marine Micropaleontology* 47, 177–226.
- Dalby, A.P., Patterson, R.T., Haggart, J.W., 2009. Distribution of Albian–Cenomanian Foraminifera from Queen Charlotte Islands, British Columbia, Canada: constraints on the timing of the northward migration of the Wrangellia terrane. *Journal of Foraminiferal Research* 3, 231–245.
- Dale, B., 1996. Dinoflagellate cyst ecology: Modeling and geological applications. In: Jansonius, J., McGregor, D.C. (Eds.), *Palynology: principles and applications*, volume 3. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 1249–1276.
- Dale, B., 2001. The sedimentary record of dinoflagellate cysts: looking back into the future of phytoplankton blooms. *Scientia Marina* 65, 257–272.
- Dale, B., Fjellså, A., 1994. Dinoflagellate cysts as paleoproductivity indicators: state of the art, potential, and limits. In: Zahn R., Pedersen T.F., Kaminski M.A., Labeyrie, L.L. (Eds.), *Carbon cycling in the glacial ocean: Constraints on the ocean's role in global change*. NATO ASI Series (Series I: Global Environmental Change) Volume 17. Springer, Berlin, Heidelberg, pp. 521–537.
- Damassa, S.P., 1979a. Eocene dinoflagellates from the Coastal Belt of the Franciscan Complex, northern California. *Journal of Paleontology* 53, 815–840, pls. 1–8.
- Damassa, S.P., 1979b. Danian dinoflagellates from the Franciscan Complex, Mendocino County, California. *Palynology* 3, 191–207.
- Dastas, N.R., Chamberlain Jr, J.A., Garb, M.P., 2014. Cretaceous–Paleogene dinoflagellate biostratigraphy and the age of the Clayton Formation, southeastern Missouri, USA. *Geoscience* 4, 1–29.

- Davey, R.J., Williams, G.L., 1966. The genera *Hystrichosphaera* and *Achomosphaera*. Bulletin of the British Museum (Natural History), Geology Supplement 3, 28–52, pls. 1–5, 9.
- de Coninck, J., Smit, J., 1982. Marine organic-walled micro-fossils at the Cretaceous-Tertiary boundary in the Barranco Del-Gredero (S.E. Spain). *Geologie en Mijnbouw* 61, 173–178.
- De Schepper, S., Head, M.J., Louwye, S., 2018. Pliocene dinoflagellate cyst stratigraphy, palaeoecology and sequence stratigraphy of the Tunnel-Canal Dock, Belgium. *Geological Magazine* 146, 92–112.
- de Vernal, A., 2009. Marine palynology and its use for studying nearshore environments. Institute of Physics Conference Series: Earth and Environmental Science 5, 12002.
- de Vernal, A., Goyette, C., Rodrigues, C.G., 1989. Contribution palynostratigraphique (dinokystes, pollen et spores) à la connaissance de la mer de Champlain: coupe de Saint Cézaire, Québec. *Canadian Journal of Earth Sciences* 26, 2450–2464.
- de Vernal, A., Rochon, A., Turon, J.-L., Matthiessen, J., 1997. Organic-walled dinoflagellate cysts: palynological tracers of sea-surface conditions in middle to high latitude marine environments. *Geobios* 30, 905–920.
- de Vernal, A., Radi, T., Zaragosi, S., Van Nieuwenhove, N., Rochon, A., Allan, E., De Schepper, S., Eynaud, F., Head, M.J., Limoges, A., Londeix, L., Marret-Davies, F., Matthiessen, J., Peynaud, A., Pospelova, V., Price, A., Richerol, T., 2020. Distribution of common modern dinocyst taxa in surface sediment of the Northern Hemisphere in relation to environmental parameters: the updated $n=1968$ database. *Marine Micropaleontology* 159, 101796.
- de Verteuil, L., Norris, G., 1996. Miocene dinoflagellate stratigraphy and systematics of Maryland and Virginia. *Micropaleontology* 42, 1–172.
- de Wit, R., 1943. *Hystrichosphaeridae* uit Limburgse vuursteen. *Verhandelingen van het Geologisch-Mijnbouwkundig Genootschap voor Nederland en Kolonien*, 363–392 (in Dutch).
- Deaf, A.S., Harding, I.C., Marshall, J.E.A., 2014. Cretaceous (Albian-?early Santonian) palynology and stratigraphy of the Abu Tunis 1x borehole, northern Western Desert, Egypt. *Palynology* 38, 51–77.
- Deflandre, G., 1935. Considérations biologiques sur les microorganismes d'origine planctonique conservés dans les silex de la craie. *Bulletin Biologique de la France et de la Belgique* 69, 213–244, pls. 5–9 (in French).
- Deflandre, G., 1937. Microfossiles des silex crétacés. Deuxième partie. Flagellés incertae sedis. *Hystrichosphaeridés*. *Sarcodinés*. *Organismes divers*. *Annales de Paléontologie* 26, 51–103 (also labelled 3–55), pls. 11–18 (also labelled pls. 8–15) (in French).

- Deflandre, G., 1947a. Sur une nouvelle hystrichosphère des silex crétacés et sur les affinités du genre *Cannosphaeropsis* O. We. Comptes rendus Hebdomadaires des Séances de l'Académie des Sciences 224, 1574–1576 (in French).
- Deflandre, G., Cookson, I.C., 1955. Fossil microplankton from Australian late Mesozoic and Tertiary sediments. Australian Journal of Marine and Freshwater Research 6, 242–313, pls 1–9.
- del Río, C.J., Concheyro, A., Martínez, S.A., 2011. The Maastrichtian–Danian at General Roca (Patagonia, Argentina): A reappraisal of the chronostratigraphy and biostratigraphy of a type locality. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 259, 129–156.
- Dias-Brito, D., 2000. Global stratigraphy, palaeobiogeography and palaeoecology of Albian–Maastrichtian pithonellid calcispheres: Impact on Tethys configuration. Cretaceous Research 21, 315–349.
- Dickens, G.R., Backman, J., 2013. Core alignment and composite depth scale for the lower Paleogene through uppermost Cretaceous interval at Deep Sea Drilling Project Site 577. Newsletters on Stratigraphy 46, 47–68.
- Dillhoff, R.M., Oillhoff, T.A., Greenwood, D.R., Devore, M.L., Pigg, K.B., 2013. The Eocene Thomas Ranch flora, Allenby Formation, Princeton, British Columbia, Canada. Botany 91, 514–529.
- Dodsworth, P., 2000. Trans-Atlantic dinoflagellate cyst stratigraphy across the Cenomanian–Turonian (Cretaceous) stage boundary. Journal of Micropalaeontology 19, 69–84.
- Dodsworth, P., 2004. The palynology of the Cenomanian–Turonian (Cretaceous) boundary succession at Aksudere in Crimea, Ukraine. Palynology 28, 129–141.
- Dodsworth, P., Eldrett, J.S., 2019. A dinoflagellate cyst zonation of the Cenomanian and Turonian (Upper Cretaceous) in the Western Interior, United States. Palynology 43, 701–723.
- Doh, S.J., King, J.W., Leinen, M., 1988. A rock-magnetic study of giant piston core LL44-GPC3 from the central North Pacific and its paleoceanographic implications. Paleoceanography 3, 89–111.
- Downie, C., Sarjeant, W.A.S., 1965. Bibliography and index of fossil dinoflagellates and acritarchs. Geological Society of America, Memoirs 94, 1–180 (Cover date December, 1964; issue date January, 1965).
- Downie, C., Hussain, M.A., Williams, G.L., 1971. Dinoflagellate cyst and acritarch associations in the Paleogene of southeast England. Geoscience and Man 3, 29–35.

- Drugg, W.S., 1967. Palynology of the upper Moreno Formation (Late Cretaceous–Paleocene) Escarpado Canyon, California. *Palaeontographica*, Abteilung B 120, 1–71, 9 pls.
- Duxbury, S., 1980. Barremian phytoplankton from Speeton, east Yorkshire. *Palaeontographica*, Abteilung A, 173, 107–146, pls. 1–13.
- Dybckjær, K., 2004. Morphological and abundance variations in *Homotryblium*-cyst assemblages related to depositional environments; uppermost Oligocene–lower Miocene, Jylland, Denmark. *Palaeogeography, Palaeoclimatology, Palaeoecology* 206, 41–58.
- Edwards, A.R., 1966. Calcareous nannoplankton from the uppermost Cretaceous and lowermost Tertiary of the mid-Waipara section, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics* 9, 481–490.
- Edwards, L.E., 1996. Graphic correlation of the Marlboro Clay and Nanjemoy Formation (uppermost Paleocene and lower Eocene) of Virginia and Maryland. In: Jansonius, J., McGregor, D.C. (Eds.), *Palynology: principles and applications*, vol. 3. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 989–999.
- Edwards, A.W.F., Cavalli-Sforza, L.L., 1964. Reconstruction of evolutionary trees. In: Heywood, V.H., McNeill, J. (Eds.), *Phenetic and phylogenetic classification*. Systematics Association, London, pp. 67–76.
- Egger, H., Mohamed, O., 2010. A slope-basin model for early Paleogene deep-water sedimentation (Achtal Formation nov. nom.) at the Tethyan continental margin (Ultrahelvetic realm) of the European Plate (eastern Alps, Germany). *Australian Journal of Earth Sciences* 103, 121–137.
- Egger, H., Koeberl, C., Wagreich, M., Stradner, H., 2009. The Cretaceous–Paleogene (K/Pg) boundary at Gams, Austria: Nannoplankton stratigraphy and geochemistry of a bathyal northwestern Tethyan setting. *Stratigraphy* 6, 333–347.
- Ehrenberg, C.G., 1837. Über das Massenverhältniss der jetzt lebenden Kiesel-Infusorien und über ein neues Infusorien-Conglomerat als Polierschiefer von Jastraba in Ungarn. *Königlich Akademie der Wissenschaften zu Berlin, Abhandlungen*, 1836 1, 109–135, pls. 1–2.
- Ehrendorfer, T., Aubry, M.-P., 1992. Calcareous nannoplankton changes across the Cretaceous/Paleocene boundary in the southern Indian Ocean (Site 750). In: Wise Jr., S.W., Palmer Julson, A.A., Schlich, R., Thomas, E. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results* 120, College Station, Texas, pp. 451–470.
- Eisenack, A., 1938. Die Phosphoritknollen der Bernsteinformation als Überlieferer tertiären Planktons. *Schriften der Physikalisch-Ökonomischen Gesellschaft zu Königsberg* 70, 181–188 (in German).
- Elbrächter, M., Gottschling, M., Hildebrand-Habel, T., Keupp, H., Kohring, R., Lewis, J., Meier,

- K.J.S., Montresor, M., Streng, M., Versteegh, G.J.M., Willems, H., Zonneveld, K., 2008. Establishing an agenda for calcareous dinoflagellate research (Thoracosphaeraceae, Dinophyceae) including a nomenclatural synopsis of generic names. *Taxon* 57, 1289–1303.
- Ellegaard, M., Lewis, J., Harding, I., 2002. Cyst–theca relationship, life cycle, and effects of temperature and salinity on the cyst morphology of *Gonyaulax baltica* sp. nov. (Dinophyceae from the Baltic Sea area). *Journal of Phycology* 38, 775–789.
- Elliot, D.H., Askin, R.A., Kyte, F.T., Zinsmeister, W.J., 1994. Iridium and dinocysts at the Cretaceous-Tertiary boundary on Seymour Island, Antarctica: implications for the K-T event. *Geology* 22, 675–678.
- Elliott, L.L., Mindell, R.A., Stockey, R.A., 2006. *Beardia vancouverensis* gen. et sp. nov. (Juglandaceae): permineralized fruits from the Eocene of British Columbia. *American Journal of Botany* 93, 557–565.
- Eldrett, J.S., Harding, I.C., 2009. Palynological analyses of Eocene to Oligocene sediments from DSDP Site 338, Outer Vøring Plateau. *Marine Micropaleontology* 73, 226–240.
- Elsik, W.C., 1977. *Paralecaniella indentata* (Defl. & Cooks. 1955) Cookson & Eisenack 1970 and allied dinocysts. *Palynology* 1, 95–102.
- England, T.D.J. 1990. Late Cretaceous to Paleogene evolution of the Georgia Basin, southwestern British Columbia (unpubl. PhD thesis). Memorial University of Newfoundland, St. John's, Newfoundland and Labrador, Canada, 481 pp.
- England, T.D.J., Bustin, R.M., 1998. Architecture of the Georgia Basin southwestern British Columbia. *Bulletin of Canadian Petroleum Geology* 46, 288–320.
- England, T.D.J., Currie, L.D., Massey, N.W.D., Roden-Tice, K.K., Miller, D.S., 1997. Apatite fission-track dating of the Cowichan fold and thrust system, southern Vancouver Island, British Columbia. *Canadian Journal of Earth Sciences* 34, 635–645.
- Engel, E.R., 1992. Palynologische Evidenz klimarelevanter Ereignisse in miozänen Sedimenten des Nordatlantiks. *Geologisches Jahrbuch, Reihe A* 125, 3–139 (in German).
- Enkin, R.J., Baker, J., Mustard, P.S., 2001. Paleomagnetism of the Upper Cretaceous Nanaimo Group, southwestern Canadian Cordillera. *Canadian Journal of Earth Sciences* 38, 1403–1422.
- Enkin, R.J., Mahoney, J.B., Baker, J., Riesterer, J., Haskin, M.L., 2003. Deciphering shallow paleomagnetic inclinations: 2. Implications from Late Cretaceous strata overlapping the Insular/Intermontane Superterrane boundary in the southern Canadian Cordillera. *Journal of Geophysical Research* 108, EPM1–EPM19.
- Erkmen, U., Sadek, A., 1981. Contribution to the stratigraphy of the Germav Formation, (Late

- Cretaceous-early Tertiary), in SE Turkey by means of dinoflagellates and nannoplankton. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte* 3, 129–140.
- Eshet, Y., Moshkovitz, S., Habib, D., Benjamini, C., Magaritz, M., 1992. Calcareous nannofossil and dinoflagellate stratigraphy across the Cretaceous/Tertiary boundary at Hor Hahar, Israel. *Marine Micropaleontology* 18, 199–228.
- Eshet, Y., Hoek, R., Almogi-Labin, A., 1994. A new dinocyst-based biostratigraphic framework for Campanian–Maastrichtian organic rich-carbonate sequences in Israel. Geological Survey of Israel, Report GSI/2/94, 24 pp.
- Esmeray-Senlet, S., Özkan-Altiner, S., Altiner, D., Miller, K.G., 2015. Planktonic foraminiferal biostratigraphy, microfacies analysis, sequence stratigraphy, and sea-level changes across the Cretaceous–Paleogene boundary in the Haymana Basin, Central Anatolia, Turkey. *Journal of Sedimentary Research* 85, 489–508.
- Esmeray-Senlet, S., Miller, K.G., Sherrell, R.M., Senlet, T., Vellekoop, J., Brinkhuis, H., 2017. Iridium profiles and delivery across the Cretaceous/Paleogene boundary. *Earth and Planetary Science Letters* 457, 117–126.
- Evans, P.R., 1966. Mesozoic stratigraphic palynology in Australia. *Australasian Oil and Gas Journal* 12, 58–63.
- Evans, N.J., Ahrens, T.J., Gregoire, D.C., 1995. Fractionation of ruthenium from iridium at the Cretaceous–Tertiary boundary. *Earth and Planetary Science Letters* 134, 141–153.
- Evitt, W.R., 1973. Maestrichtian *Aquilapollenites* in Texas, Maryland, and New Jersey. *Geoscience and Man* 7, 31–38, 2 pls.
- Evitt, W.R., 1985. Sporopollenin and dinoflagellate cysts: their morphology and interpretation. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, 333 pp.
- Evitt, W.R., Damassa, S.P., Albert, N.R., 1998. A tiger by the tail: The exophragm of the Cretaceous–Paleocene dinoflagellate *Palaeoperidinium* and its implications. *Palynology*. 22, 1–55.
- Falkowski, P.G., Katz, M.E., Knoll, A.H., Quigg, A., Raven, J.A., Schofield, O., Taylor, F.J.R., 2004. The evolution of modern eukaryotic phytoplankton. *Science* 305, 354–360.
- Fanti, F., Catuneanu, O., 2009. Stratigraphy of the Upper Cretaceous Wapiti Formation, west-central Alberta, Canada. *Canadian Journal of Earth Sciences* 46, 263–286.
- Fanti, F., Bell, P.R., Sissons, R.L., 2013. A diverse, high-latitude ichnofauna from the Late Cretaceous Wapiti Formation, Alberta, Canada. *Cretaceous Research* 41, 256–269.
- Faris, M., Farouk, S., 2012. Integrated biostratigraphy of two upper Maastrichtian–Palaeocene

- successions in north-central Sinai, Egypt. *Geologia Croatica* 65, 139–160.
- Farouk, S., Jain, S., 2016. Benthic foraminiferal response to relative sea-level changes in the Maastrichtian–Danian succession at the Dakhla Oasis, Western Desert, Egypt. *Geological Magazine* 155, 729–746.
- Fensome, R.A., Williams, G.L., 2005. Scotian margin PalyAtlas, version 1. Geological Survey of Canada, Open File 4677.
- Fensome, R.A., Jansonius, J., Skog, J.E., 1998. Proposals to amend provisions regarding typification of the names of fossil plants. *Taxon*. 47, 489–490.
- Fensome, R.A., Nøhr-Hansen, H., Williams, G.L., 2016. Cretaceous and Cenozoic dinoflagellate cysts and other palynomorphs from the western and eastern margins of the Labrador–Baffin Seaway. *Geological Survey of Denmark and Greenland Bulletin*, 36, 1–143.
- Fensome, R.A., Williams, G.L., MacRae, R.A., 2009. Late Cretaceous and Cenozoic fossil dinoflagellates and other palynomorphs from the Scotian Margin, offshore eastern Canada. *Journal of Systematic Palaeontology* 7, 1–79.
- Fensome, R.A., Williams, G.L., MacRae, R.A., 2019. The Lentin and Williams index of fossil dinoflagellates 2019 edition. American Association of Stratigraphic Palynologists, Contribution Series 50, 1173 pp.
- Fensome, R.A., MacRae, J.M., Moldowan, F.J.R., Williams, G.L., 1996. The early Mesozoic radiation of dinoflagellates. *Paleobiology* 22, 329–338.
- Fensome, R.A., Taylor, F.J.R., Norris, G., Sarjeant, W.A.S., Wharton, D.I., Williams, G.L., 1993. A classification of fossil and living dinoflagellates. *Micropaleontology*, Special Publication 7, 1–351.
- Fensome, R.A., Crux, J.A., Gard, I.G., Macrae, R.A., Williams, G.L., Thomas, F.C., Fiorini, F., Wach, G., 2008. The last 100 million years on the Scotian Margin, offshore eastern Canada: an event-stratigraphic scheme emphasizing biostratigraphic data. *Atlantic Geology* 44, 93–126.
- Ferguson, S., Warny, S., Escarguel, G., Mudie, P.J., 2018. MIS 5-1 dinoflagellate cyst analyses and morphometric evaluation of *Galeacysta etrusca* and *Spiniferites cruciformis* in southwestern Black Sea. *Quaternary International* 465, 117–129.
- Finkel, Z.V., Sebbo, J., Feist-Burkhardt, S., Irwin, A.J., Katz, M.E., Schofield, O.M.E., Young, J.R., Falkowski, P.G., 2007. A universal driver of macroevolutionary change in the size of marine phytoplankton over the Cenozoic. *Proceeding of the National Academy of Sciences of the United States of America* 104, 20416–20420.
- Firth, J.V., 1987. Dinoflagellate biostratigraphy of the Maastrichtian to Danian interval in the

- U.S. Geological Survey Albany Core, Georgia, U.S.A. *Palynology* 11, 199–216.
- Firth, J. V., 1993. Dinoflagellate assemblages and sea-level fluctuations in the Maastrichtian of southwest Georgia. *Review of Palaeobotany and Palynology* 79, 179–204.
- Firth, J.V., 1996. Upper middle Eocene to Oligocene dinoflagellate biostratigraphy and assemblage variations in Hole 913B, Greenland Sea. In: Thiede, J., Myhre, A.M., Firth, J.V., Johnson, G.L., Ruddimann, W.F. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, 151, College Station, Texas, pp. 203–242.
- FitzPatrick, M.E.J., Forber, D.A., Hart, M.B., 2017. Dinocyst stratigraphy and palaeoenvironmental interpretation of the Cretaceous/Paleogene boundary at Stevns Klint, Denmark. *Cretaceous Research* 87, 408–421.
- Föllmi, K.B., 2012. Early Cretaceous life, climate and anoxia. *Cretaceous Research* 35, 230–257.
- Frederiksen, N.O., 1987. Tectonic and paleogeographic setting of a new latest Cretaceous floristic province in North America. *PALAIOS* 2, 533–542.
- Frederiksen, N.O., 1991. Pollen zonation and correlation of Maastrichtian marine beds and associated strata, Ocean Point dinosaur locality, North Slope, Alaska. *United States Geological Survey Bulletin* 1990–E, E1–E24, pls. 1–7.
- Frieling, J., Sluijs, A., 2018. Towards quantitative environmental reconstructions from ancient non-analogue microfossil assemblages: Ecological preferences of Paleocene–Eocene dinoflagellates. *Earth-Science Reviews* 185, 956–973.
- Fry, B., Sherr, E.B., 1984. $\delta^{13}\text{C}$ measurements as indicators of carbon flow in marine and freshwater ecosystems. *Contributions in Marine Science* 27, 13–47.
- Fütterer, D., 1976. Kalkige Dinoflagellaten (“Calciodinelloideae”) und die systematische Stellung der Thoracosphaeroideae. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 151, 119–141 (in German).
- Fütterer, D., 1978. Distribution of calcareous dinoflagellates in Cenozoic sediments of Site 366, eastern North Atlantic. *Deep Sea Drilling Project, Initial Reports* 41, 709–737.
- Fütterer, D., 1990. Distribution of calcareous dinoflagellates at the Cretaceous-Tertiary boundary of Queen Maud Rise, eastern Weddell Sea, Antarctica (ODP Leg 113). In: Barker, P.F., Kennett, J.P., O’Connell, S., Pisias, N. G. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, Texas, 113, pp. 533–548.
- Galeotti, S., Brinkhuis, H., Huber, M., 2004. Records of post-Cretaceous-Tertiary boundary millennial-scale cooling from the western Tethys: A smoking gun for the impact-winter hypothesis? *Geology* 32, 529–532.

- Gamero, J.C., Archangelsky, S., 1981. Palinozonas Neocretácicas y Terciarias de la plataforma continental Argentina en la Cuenca del Colorado. *Revista Española de Micropaleontología* 13, 119–140 (in Spanish).
- Gardin, S., Monechi, S., 1998. Palaeoecological change in middle to low latitude calcareous nannoplankton at the Cretaceous/Tertiary boundary. *Bulletin de la Société Géologique de France* 169, 709–723.
- Garg, R., Khawaja-Ateequzaman, Prasad, V., 2006. Significant dinoflagellate cyst biohorizons in the Upper Cretaceous–Palaeocene succession of the Khasi Hills, Meghalaya. *Journal of the Geological Society of India* 67, 737–747.
- Gearing, P., Plucker, F.E., Parker, P.L., 1977. Organic carbon stable isotope ratios of continental margin sediments. *Marine Chemistry* 5, 251–266.
- Gedl, P., 2004. Dinoflagellate cyst record of the deep-sea Cretaceous–Tertiary boundary at Uzgruň, Carpathian Mountains, Czech Republic. *Geological Society, London, Special Publications* 230, 257–273.
- Gerstel, J., Thunell, R.C., Zachos, J.C., Arthur, M.A., 1986. The Cretaceous/Tertiary boundary event in the North Pacific: Planktonic foraminiferal results from Deep Sea Drilling Project Site 577, Shatsky Rise. *Paleoceanography* 1, 97–117.
- Ghourchaei, S., Ghasemi-Nejad, E., Vahidinia, M., Ashouri, A., 2015. Paleoenvironmental reconstruction of the Upper Cretaceous succession (Abtalkh Formation) of the Kopeh-Dagh Basin, northeastern Iran based on foraminiferal and palynological analyses. *Arabian Journal of Geosciences*, 8, 2153–2168.
- Gibson, D.W., 1985. Stratigraphy, sedimentology and depositional environments of the coal-bearing Jurassic–Cretaceous Kootenay Group, Alberta and British Columbia. *Geological Survey of Canada, Bulletin* 357, 108 pp.
- Gini, C., 1912. Variabilità e mutabilità. In: Pizetti, E., Salvemini, T. (Eds.), *Memorie di Metodologica Statistica*. Libreria Eredi Virgilio Veschi, Rome, pp. 211–382.
- Goderis, S., Tagle, R., Belza, J., Smit, J., Montanari, A., Vanhaecke, F., Erzinger, J., Claeys, P., 2013. Reevaluation of siderophile element abundances and ratios across the Cretaceous–Paleogene (K–Pg) boundary: Implications for the nature of the projectile. *Geochimica et Cosmochimica Acta* 120, 417–446.
- Goñi, M.A., Teixeira, M.J., Perkeya, D.W., 2003. Sources and distribution of organic matter in a river-dominated estuary (Winyah Bay, SC, USA). *Estuarine, Coastal and Shelf Science* 57, 1023–1048.
- Golovneva, L.B., 1994. Maastrichtian–Danian floras of Koryak Upland. *Russian Academy of Sciences, Proceedings of Komarov Botanical Institute* 13, 1–146.

- Gordon, W.A., 1973. Marine life and ocean surface currents in the Cretaceous. *Journal of Geology* 81, 269–284.
- Górka, H., 1963. Coccolithophoridés, dinoflagellés, hystrichosphaeridés et microfossiles incertae sedis du Crétacé supérieur de Pologne. *Acta Palaeontologica Polonica* 8, 3–90, pls 1–11 (in French).
- Grega, L., Anderson, S., Cheetham, M., Clemente, M., Colletti, A., Moy, W., Talarico, D., Thatcher, S.L., Osborn, J.M., 2013. Aerodynamic characteristics of saccate pollen grains. *International Journal of Plant Sciences* 174, 499–510.
- Grey, M., Haggart, J.W., Smith, P.L., 2008. Species discrimination and evolutionary mode of *Bucha* (Bivalvia: Buchiidae) from Upper Jurassic–Lower Cretaceous strata of Grassy Island British Columbia, Canada. *Palaeontology* 51, 583–595.
- Grey, M., Haggart, J.W., Jeletzky, J.A., 2007. Uppermost Jurassic (Tithonian) to Lower Cretaceous (Valanginian) section at Grassy Island, west coast Vancouver Island, British Columbia. Geological Survey of Canada, Open File 5666, 52 pp.
- Grimm, E.C., 1991–2019. Tilia software. Version 2.6.1. Illinois State Museum, Springfield, Illinois.
- Guasti, E., Speijer, R.P., Brinkhuis, H., Smit, J., Steurbaut, E., 2006. Paleoenvironmental change at the Danian–Selandian transition in Tunisia: Foraminifera, organic-walled dinoflagellate cyst and calcareous nannofossil records. *Marine Micropaleontology* 59, 210–229.
- Guédé, K.É., Slimani, H., Louwye, S., Asebriy, L., Toufiq, A., Ahmamou, M., Hassani, I.-E.E.A.E., Digbehi, Z.B., 2014. Organic-walled dinoflagellate cysts from the Upper Cretaceous–lower Paleocene succession in the western External Rif, Morocco: New species and new biostratigraphic results. *Geobios* 47, 291–304.
- Guerra, R.M., Concheyro, A., Kochhann, K.G.D., Bom, M.H.H., Ceolin, D., Musso, T., Savian, J.F., Fauth, G., 2021. Calcareous microfossils and paleoenvironmental changes across the Cretaceous–Paleogene (K–Pg) boundary at the Cerro Azul section, Neuquén Basin, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology* 567, 110217.
- Guerstein, G.R., 1990. Palinología estratigráfica del Terciario de la Cuenca del Colorado, Republica Argentina Parte III: Estudio sistemático y estadístico de la perforación Puerto Belgrano N.º 20. *Revista Española de Micropaleontología* 22, 459–480 (in Spanish).
- Guerstein, G.R., Williams, G.L., Fensome, R.A., 2001. *Cannosphaeropsis quattrocchiaie*, a new species of dinoflagellate cyst from the mid Cenozoic of the Colorado Basin, Argentina. *Micropaleontology* 47, 155–167.
- Guerstein, G.R., Guler, M.V., Casadío, S., 2004. Palynostratigraphy and palaeoenvironments

- across the Oligocene-Miocene boundary within the Centinela Formation, southwestern Argentina. Geological Society of London, Special Publications 230, 325–343.
- Guiot, J., 1990. Methods and programs of statistics for paleoclimatology and paleoecology, in: Guiot, J., Labeyrie, L. (Eds.), *Quantification Des Changements Climatiques: Methodes et Programmes*. Monographie No 1. Institut National des Sciences de l'Univers (INSU-France), Paris, 253 pp.
- Guler, M.V., Borel, C.M., Brinkhuis, H., Navarro, E., Astini, R., 2014. Brackish to freshwater dinoflagellate cyst assemblages from the La Colonia Formation (Paleocene?), northeastern Patagonia, Argentina. *Ameghiniana* 51, 141–153.
- Guler, M.V., González Estebenet, M.S., Navarro, E.L., Astini, R.A., Pérez Panera, J.P., Ottone, E.G., Pieroni, D., Paolillo, M.A., 2019. Maastrichtian to Danian Atlantic transgression in the north of Patagonia: A dinoflagellate cyst approach. *Journal of South American Earth Sciences* 92, 552–564.
- Gurdebeke, P.R., Pospelova, V., Mertens, K.N., Dallimore, A., Chana, J., Louwye, S., 2018. Diversity and distribution of dinoflagellate cysts in surface sediments from fjords of western Vancouver Island (British Columbia, Canada). *Marine Micropaleontology* 143, 12–29.
- Gurdebeke, P.R., Mertens, K.N., Meyvisch, P., Bogus, K., Pospelova, V., Louwye, S., 2020. *Hiddenocysta matsuoekae* gen. et sp. nov. from the Holocene of Vancouver Island, British Columbia, Canada. *Palynology* 45, 103–114.
- Gushulak, C.A.C., West, C.K., Greenwood, D.R., 2016. Paleoclimate and precipitation seasonality of the early Eocene McAbee megaflora, Kamloops Group, British Columbia. *Canadian Journal of Earth Sciences* 53, 591–604.
- Habib, D., Saeedi, F., 2007. The *Manumiella seelandica* global spike: Cooling during regression at the close of the Maastrichtian. *Palaeogeography, Palaeoclimatology, Palaeoecology* 255, 87–97.
- Habib, D., Olsson, R.K., Chengie Liu, Moshkovitz, S., 1996. High-resolution biostratigraphy of sea-level low, biotic extinct and chaotic sedimentation at the Cretaceous-Tertiary boundary in Alabama, north of the Chicxulub Crater. Geological Society of America, Special Papers 307, 243–252.
- Haeckel, E., 1894. Systematische Phylogenie. Entwurf eines natürlichen Systems der Organismen auf Grund ihrer Stammesgeschichte, I. Systematische Phylogenie der Protisten und Pflanzen. Reimer, Berlin, XV + 400 pp (in German).
- Haggart, J.W., 1991. A synthesis of Cretaceous stratigraphy, Queen Charlotte Islands, British Columbia. In: Woodsworth, G.J. (Ed.), *Evolution and hydrocarbon potential of the Queen Charlotte Basin, British Columbia*. Geological Survey of Canada, Paper 90–10, pp. 253–277.

- Haggart, J.W., 1993. Latest Jurassic and Cretaceous paleogeography of the northern Insular Belt, British Columbia. In: Dunne, G.C., McDougall, K.A. (Eds.), *Mesozoic paleogeography of the western United States. II. Society of Economic Paleontologists and Mineralogists, Pacific Section, Special Volume*, pp. 463–475.
- Haggart, J.W., Carter, E.S., 1993. Cretaceous (Barremian-Aptian) Radiolaria from Queen Charlotte Islands, British Columbia: newly recognized faunas and stratigraphic implications. *Geological Survey of Canada, Current Research, Part E, Paper 93-1E*, 55–65.
- Haggart, J.W., Graham, R., 2018. The crinoid *Marsupites* in the Upper Cretaceous Nanaimo Group, British Columbia: Resolution of the Santonian–Campanian boundary in the North Pacific Province. *Cretaceous Research* 87, 277–295.
- Haggart, J.W., Ward, P.D., Orr, W., 2005. Turonian (Upper Cretaceous) lithostratigraphy and biochronology, southern Gulf Islands, British Columbia, and northern San Juan Islands, Washington State. *Canadian Journal of Earth Sciences* 42, 2001–2020.
- Haggart, J.W., Graham, R., Beard, G., 2011. Field Trip 2. The Upper Cretaceous of the Nanaimo–Courtenay region of Vancouver Island. In: Haggart, J.W., Smith, P.L. (Eds.), *Field trips to Harrison Lake and Vancouver Island, British Columbia. Twenty-first Canadian paleontology conference, field trip guidebook No. 16*. University of British Columbia, Vancouver, pp. 31–62.
- Haggart, J.W., Ward, P.D., Raub, T.D., Carter, E.S., Kirschvink, J.L., 2009. Molluscan biostratigraphy and paleomagnetism of Campanian strata, Queen Charlotte Islands, British Columbia: implications for Pacific coast North America biochronology. *Cretaceous Research* 30, 939–951.
- Haggart, J.W., Hessin, W.A., McGugan, A., Bowen, D.R., Beard, G., Ludvigsen, R., Obear, T., 1997. Paleoenvironment and age of newly-recognized Tertiary marine strata, east coast Vancouver Island, British Columbia. *Second British Columbia paleontological symposium, program and abstracts*. British Columbia Paleontological Alliance, May 9–11, Vancouver, British Columbia, 25.
- Haggart, J.W., Squires, R.L., McNeil, D., Mahoney, J.B., Mustoe, G.E., Sweet, A.S., Cockburn, T., Hessin, W., Williams, J.B., and Bowen, D.R., in prep. Paleocene stratigraphy and fauna of southeast Vancouver Island, British Columbia: shallow marine infilling of the post-Cretaceous forearc basin. *Canadian Journal of Earth Sciences*.
- Hansen, J.M., 1977. Dinoflagellate stratigraphy and echinoid distribution in Upper Maastrichtian and Danian deposits from Denmark. *Bulletin of the Geological Society of Denmark* 26, 1–26.
- Hansen, H.J., Gwosdz, R., Hansen, J.M., Bromley, R., Rasmussen, K.L., 1986. The diachronous C-T plankton extinction in the Danish Basin. In: Walliser, O.H. (Ed.), *Global bio-events*:

- lecture notes in earth science, 8. Springer, Berlin, pp. 381–384.
- Haq, B.U., Hardenbol, J., Vail, P.R., Stover, L.E., Colin, J.P., Ioannides, N.S., Wright, R.C., Baum, G.R., Gombos Jr., A.M., Pflum, C.E., Loutit, T.S., Jan du Chêne, R., Romine, K.K., Sarg, J.F., Posamentier, H.W., Morgan, B.E., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. Society of Economic Paleontologists and Mineralogists Special Publication 42, 71–108.
- Harada, K., Matsuoka, K., 1974. Dinoflagellata and acritarcha: An introduction to fossil dinoflagellates and acritarchs. News of Osaka Micropaleontologists, Special Volume 1, 1–60.
- Harker, S.D., Sarjeant, W.A.S., Caldwell, W.G.E., 1990. Late Cretaceous (Campanian) organic-walled microplankton from the interior plains of Canada, Wyoming and Texas: biostratigraphy, palaeontology and palaeoenvironmental interpretation. *Palaeontographica, Abteilung B* 219, 243 pp., pls. 1–13.
- Harding, I.C., 1990. A dinocyst calibration of the European Boreal Barremian. *Palaeontographica, Abteilung B Palaeophytologie* 218, 1–76.
- Harding, I.C., Charles, A.J., Marshall, J.E.A., Pälike, H., Roberts, A.P., Wilson, P.A., Jarvis, E., Thorne, R., Morris, E., Moremon, R., Pearce, R.B., Akbari, S., 2011. Sea-level and salinity fluctuations during the Paleocene–Eocene thermal maximum in Arctic Spitsbergen. *Earth and Planetary Science Letters* 303, 97–107.
- Harland, R., 1973. Dinoflagellate cysts and acritarchs from the Bearpaw Formation (Upper Campanian) of southern Alberta, Canada. *Palaeontology* 16, 665–706, pls. 84–88.
- Harland, R., 1982. Recent dinoflagellate cyst assemblages from the southern Barents Sea. *Palynology* 6, 9–18.
- Harland, R., 1983. Distribution maps of Recent dinoflagellate cysts in bottom sediments from the North Atlantic Ocean and adjacent seas. *Palaeontology* 26, 321–387.
- Harland, R., Bonny, A.P., Hughes, M.J., Morigi, A.N., 1991. The lower Pleistocene stratigraphy of the Ormesby borehole, Norfolk, England. *Geological Magazine* 128, 647–660.
- Harris, A.J., Tocher, B.A., 2003. Palaeoenvironmental analysis of Late Cretaceous dinoflagellate cyst assemblages using high-resolution sample correlation from the Western Interior Basin, USA. *Marine Micropaleontology* 48, 127–148.
- Hart, B.S., Plint, A.G., 2003. Stratigraphy and sedimentology of shoreface and fluvial conglomerates: insights from the Cardium Formation in NW Alberta and adjacent British Columbia. *Bulletin of Canadian Petroleum Geology* 51, 437–464.
- Hart, M.B., Feist, S.E., Price, G.D., Leng, M.J., 2004. Reappraisal of the K–T boundary

- succession at Stevns Klint, Denmark. *Journal of the Geological Society*, London 161, 885–892.
- Hay, W.W., 2009. Cretaceous oceans and ocean modeling. *Society of Economic Paleontologists and Mineralogists Special Publication* 91, 243–271.
- Hay, W.W., Floegel, S., 2012. New thoughts about the Cretaceous climate and oceans. *Earth-Science Reviews* 115, 262–272.
- He Chengquan, H., 1991. Late Cretaceous–early Tertiary microphytoplankton from the western Tarim Basin in southern Xinjiang, China. *Nanjing Institute of Geology and Palaeontology, Academia Sinica*, 235 pp., 65 pls. (in Chinese).
- Head, M.J., 1993. Dinoflagellates, sporomorphs, and other palynomorphs from the upper Pliocene St. Erth Beds of Cornwall, southwestern England. *Journal of Paleontology*, *Paleontological Society Memoir* 67, 1–62.
- Head, M.J., 2007. Last Interglacial (Eemian) hydrographic conditions in the southwestern Baltic Sea based on dinoflagellate cysts from Ristinge Klint, Denmark. *Geological Magazine* 144, 987–1013.
- Head, M.J., 1996. Modern dinoflagellate cysts and their biological affinities. In: Jansonius, J., McGregor, D.C. (Eds.), *Palynology: principles and applications*, volume 3. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 1197–1248.
- Head, M.J., Wrenn, J.H., 1992. A forum on Neogene and Quaternary dinoflagellate cysts. In: Head, M.J., Wrenn, J.H. (Eds.), *Neogene and Quaternary dinoflagellate cysts and acritarchs*. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 1–31.
- Head, M.J., Seidenkrantz, M.-S., Janczyk-Kopikowa, Z., Marks, L., Gibbard, P.L., 2005. Last Interglacial (Eemian) hydrographic conditions in the southeastern Baltic Sea, NE Europe, based on dinoflagellate cysts. *Quaternary International* 130, 3–30.
- Heath, G.R., 1985. Paleomagnetism and accumulation rates of sediments at Site 577 and 578, Deep Sea Drilling Project Leg 86, western North Atlantic. *Deep Sea Drilling Project, Initial Reports* 86, 459–502.
- Heilmann-Clausen, C., 1985. Dinoflagellate stratigraphy of the uppermost Danian to Ypresian in the Viborg I borehole, central Jylland, Denmark. *Danmarks Geologiske Undersøgelse, Serie A* 7, 1–69.
- Heilmann-Clausen, C., Thomsen, E., 1995. Barremian–Aptian dinoflagellates and calcareous nannofossils in the Ahlum 1 borehole and the Otto Gott clay pit, Sarstedt, Lower Saxony Basin, Germany. *Geologisches Jahrbuch, Reihe A* 141, 257–365.
- Heisecke, A.M., 1970. Microplancton de la Formación Roca de la Provincia de Neuquén.

- Ameghiniana 7, 225–263.
- Helby, R.J., Morgan, R., Partridge, A.D., 1987. A palynological zonation of the Australian Mesozoic; studies in Australian Mesozoic palynology. *Association of Australasian Palaeontologists, Memoir* 4, 1–94.
- Helenes, J., Téllez-Duarte, M.A., 2002. Paleontological evidence of the Campanian to early Paleocene paleogeography of Baja California. *Palaeogeography, Palaeoclimatology, Palaeoecology* 186, 61–80.
- Henriksson, A.S., 1996. Calcareous nannoplankton productivity and succession across the Cretaceous-Tertiary boundary in the Pacific (DSDP Site 465) and Atlantic (DSDP Site 527) oceans. *Cretaceous Research* 17, 451–477.
- Hernandez-castillo, G.R., Stockey, R.A., Beard, G., 2005. Taxodiaceous pollen cones from the early Tertiary of British Columbia. *International Journal of Plant Sciences* 166, 339–346.
- Heusser, L.E., 1988. Pollen distribution in marine sediments on the continental margin off northern California. *Marine Geology* 80, 131–147.
- Hewaidy, A.G.A., Farouk, S., Bazeen, Y.S., 2019. Foraminiferal biostratigraphy and paleoenvironments of the Danian–Selandian succession at the Kharga Oasis, Western Desert, Egypt. *Arabian Journal of Geosciences* 12, 133.
- Hildebrand-Habel, T., Streng, M., 2003. Calcareous dinoflagellate associations and Maastrichtian–Tertiary climatic change in a high-latitude core (ODP Hole 689B, Maud Rise, Weddell Sea). *Palaeogeography, Palaeoclimatology, Palaeoecology* 197, 293–321.
- Hildebrand-Habel, T., Willems, H., 2000. Distribution of calcareous dinoflagellates from the Maastrichtian to early Miocene of DSDP Site 357 (Rio Grande Rise, western South Atlantic Ocean). *International Journal of Earth Sciences* 88, 694–707.
- Hildebrand-Habel, T., Willems, H., Versteegh, G.J.M., 1999. Variations in calcareous dinoflagellate associations from the Maastrichtian to middle Eocene of the western South Atlantic Ocean (São Paulo Plateau, DSDP Leg 39, Site 356). *Review of Palaeobotany and Palynology* 106, 57–87.
- Hildebrand, A.R., Penfield, G.T., Kring, D.A., Pilkington, M., Camargo, Z.A., Jacobsen, S.B., Boynton, W. V., 1991. Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico. *Geology* 19, 867–871.
- Hill, M.O., Gauch, H.G., 1980. Detrended correspondence analysis: An improved ordination technique. *Vegetatio* 42, 47–58.
- Hoek, R.P., Eshet, Y., Almogi-Labin, A., 1996. Dinoflagellate cyst zonation of Campanian–Maastrichtian sequences in Israel. *Micropaleontology* 42, 125–150.

- Hollis, C.J., Stickley, C.E., Bijl, P.K., Schiøler, P., Clowes, C.D., Xun Li, Campbell, H., 2017. The age of the Takatika Grit, Chatham Islands, New Zealand. *Alcheringa* 41, 383–396.
- Hopkins, W.S., 1966. Palynology of Tertiary rocks of the Whatcom basin, southwestern British Columbia and northwestern Washington (unpub. PhD thesis). University of British Columbia, Vancouver, 184 pp.
- Houben, A.J.P., Quaijtaal, W., Wade, B.S., Schouten, S., Brinkhuis, H., 2019. Quantitative organic-walled dinoflagellate cyst stratigraphy across the Eocene-Oligocene transition in the Gulf of Mexico: A record of climate- and sea level change during the onset of Antarctic glaciation. *Newsletters on Stratigraphy* 52, 131–154.
- Hoyle, T.M., Sala-Pérez, M., Sangiorgi, F., 2019. Where should we draw the lines between dinocyst “species”? Morphological continua in Black Sea dinocysts. *Journal of Micropalaeontology* 38, 55–65.
- Huan Li, Habib, D. 1996. Dinoflagellate stratigraphy and its response to sea level change in Cenomanian–Turonian sections of the Western Interior of the United States. *PALAIOS* 11, 15–30.
- Hull, P.M., Franks, P.J.S., Norris, R.D., 2011. Mechanisms and models of iridium anomaly shape across the Cretaceous–Paleogene boundary. *Earth and Planetary Science Letters* 301, 98–106.
- Hull, P.M., Bornemann, A., Penman, D.E., Henahan, M.J., Norris, R.D., Wilson, P.A., Blum, P., Alegret, L., Batenburg, S.J., Bown, P.R., Bralower, T.J., Cournede, C., Deutsch, A., Donner, B., Friedrich, O., Jehle, S., Kim, H., Kroon, D., Lippert, P.C., Lorocho, D., Moebius, I., Moriya, K., Peppe, D.J., Ravizza, G.E., Röhl, U., Schueth, J.D., Sepúlveda, J., Sexton, P.F., Sibert, E.C., Śliwińska, K.K., Summons, R.E., Thomas, E., Westerhold, T., Whiteside, J.H., Yamaguchi, T., Zachos, J.C., 2020. On impact and volcanism across the Cretaceous–Paleogene boundary. *Science* 367, 266–272.
- Hultberg, S.U., 1985. Systematic paleontology. In: Hultberg, S.U. (Ed.), *Dinoflagellate studies of the upper Maastrichtian and Danian in southern Scandinavia* (publ. PhD thesis). University of Stockholm, Stockholm, Sweden, pp. 104–189.
- Hultberg, S.U., 1986. Danian dinoflagellate zonation, the C-T boundary and the stratigraphical position of the Fish Clay in southern Scandinavia. *Journal of Micropalaeontology* 5, 37–47.
- Hultberg, S.U., Malmgren, B.A., 1986. Dinoflagellate and planktonic foraminiferal paleobathymetrical indices in the Boreal uppermost Cretaceous. *Micropaleontology* 32, 316–323.
- Iakovleva, A.I., 2015. Middle-late Eocene dinoflagellate cysts from NE Ukraine (Borehole No. 230, Dnepr-Donets Depression): Stratigraphic and palaeoenvironmental approach. *Acta*

Palaeobotanica 55, 19–51.

- Iakovleva, A.I., Brinkhuis, H., Cavagnetto, C., 2001. Late Palaeocene-early Eocene dinoflagellate cysts from the Turgay Strait, Kazakhstan; correlations across ancient seaways. *Palaeogeography, Palaeoclimatology, Palaeoecology* 172, 243–268.
- Imbrie, J., Kipp, N.G., 1971. A new micropaleontological method for quantitative paleoclimatology: Application to a late Pleistocene Caribbean core. In: Turkian, K.K. (Ed.), *The last Cenozoic glacial ages*. Yale University Press, New Haven, pp. 71–181.
- Imlay, R.W., 1959. Succession and speciation of the pelecypod *Aucella*. United States Geological Survey, Professional Paper. 314–G, 155–169, 19 pls.
- Imlay, R.W., 1961. Characteristic Lower Cretaceous megafossils from northern Alaska. United States Geological Survey, Professional Paper 335, 1–76.
- Imlay, R.W., Jones, D.L., 1970. Ammonites from the *Buchia* zones in northwestern California and southwestern Oregon. United States Geological Survey, Professional Paper 647–B, 1–59.
- Inokuchi, H., Heider, F., 1992. Paleolatitude of the southern Kerguelen Plateau inferred from the paleomagnetic study of the Upper Cretaceous basalts. In: Barbu, E.M. (Ed.), *Proceedings of the Ocean Drilling Program, Scientific Results 120*, College Station, Texas, pp. 89–96.
- Jafar, S.A., 1979. Taxonomy, stratigraphy and affinities of calcareous nannoplankton genus *Thoracosphaera* Kamptner. *Proceedings of the Fourth International Palynological Conference* 2, 1–21.
- Jagt-Yazykova, E.A., 2012. Ammonite faunal dynamics across bio-events during the mid- and Late Cretaceous along the Russian Pacific coast. *Acta Palaeontologica Polonica* 57, 737–748.
- Jain, K.P., 1978. An Upper Cretaceous dinoflagellate assemblage from Vriddhachalam area, Cauvery Basin, south India. *Palaeobotany* 25, 146–160.
- Jan du Chêne, R., 1987. Étude systématique des kystes de dinoflagellés de la Formation des Madeleines (Danien du Sénégal). *Cahiers de Micropaléontologie, Nouvelle Série* 2, 147–172, pls. 1–28 (in French).
- Janofske, D., Karwath, B., 2000. Oceanic calcareous dinoflagellates of the equatorial Atlantic Ocean: cyst-theca relationship, taxonomy and aspects on ecology. In: Karwath, B. (Ed.), *Ecological studies on living and fossil calcareous dinoflagellates on the equatorial and tropical Atlantic Ocean (Publ. PhD thesis)*. *Berichte aus dem Fachbereich Geowissenschaften der Universität Bremen* 152, University of Bremen, Bremen, Germany, pp. 94–136.

- Jansson, I.M., Mertens, K.N., Head, M.J., de Vernal, A., Londeix, L., Marret, F., Matthiessen, J., Sangiorgi, F., 2014. Statistically assessing the correlation between salinity and morphology in cysts produced by the dinoflagellate *Protoceratium reticulatum* from surface sediments of the North Atlantic Ocean, Mediterranean-Marmara-Black Sea region, and Baltic-Kattegat-Skag. *Palaeogeography, Palaeoclimatology, Palaeoecology* 399, 202–213.
- Jbari, H., Slimani, H., Chekar, M., Asebriy, L., Benzaggagh, M., Mahboub, I., Chakir, S., 2020. Campanian to Danian dinoflagellate cyst assemblages from the southwestern Tethyan margin (Tattofte section, western External Rif, Morocco): Biostratigraphic and paleobiogeographic interpretations. *Review of Palaeobotany and Palynology* 279, 104225.
- Jehle, S., Bornemann, A., Deprez, A., Speijer, R.P., 2015. The impact of the latest Danian event on planktic foraminiferal faunas at ODP Site 1210 (Shatsky Rise, Pacific Ocean). *PLoS One* 10, e0141644.
- Jeletzky, J.A., 1950. Stratigraphy of the west coast of Vancouver Island between Kyuquot Sound and Esperanza Inlet, British Columbia (preliminary report). *Geological Survey of Canada, Paper* 50-77, 1–52.
- Jeletzky, J.A., 1964. Lower Cretaceous marine index fossils of the sedimentary basins of western and arctic Canada. *Geological Survey of Canada, Paper* 64-11, 1–101, 1–36 pls.
- Jeletzky, J.A., 1965. Late Upper Jurassic and early Lower Cretaceous fossil zones of the Canadian western Cordillera, British Columbia. *Geological Survey of Canada, Bulletin* 103, 1–70, 22 pls.
- Jeletzky, J.A., 1970. Cretaceous macrofaunas. In: Douglas, J.R. (Ed.), *Biochronology: standard of Phanerozoic time*. Geological Survey of Canada, Economic Geology Report No. 1B. Ottawa, Ontario, pp. 649–662, pls 23–28.
- Jenkins, R.G., Hasegawa, T., Haggart, J.W., Goto, A.S., Iwase, Y., Nakase, C., 2017. Cool eastern rim of the North Pacific during Late Cretaceous time: a seep-carbonate paleothermometry from the Nanaimo Group, British Columbia, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 487, 407–415.
- Jiang, M.J., Gartner, S., 1986. Calcareous nannofossil succession across the Cretaceous/Tertiary boundary in east-central Texas. *Micropaleontology* 32, 232–255.
- Johnson, S.Y., 1984. Stratigraphy, age, and paleogeography of the Eocene Chuckanut Formation, northwest Washington. *Canadian Journal of Earth Sciences* 21, 92–106.
- Jones, D.L., 1960. Pelecypods of the genus *Pterotrigonia* from the west coast of North America. *Journal of Paleontology* 34, 433–439.
- Jones, D.L., 1963. Upper Cretaceous (Campanian and Maestrichtian) ammonites from southern Alaska. *United States Geological Survey, Professional Paper* 432, 1–53, 41 pls.

- Jonsson, C.H.W., Hebda, R.J., 2015. Macroflora, paleogeography, and paleoecology of the Upper Cretaceous (Turonian?–Santonian) Saanich Member of the Comox Formation, Saanich Peninsula, British Columbia, Canada. *Canadian Journal of Earth Sciences* 52, 519–536.
- Jost, L., 2006. Entropy and diversity. *Oikos* 113, 363–375.
- Kamptner, E., 1927. Beitrag zur Kenntnis adriatischer Coccolithophoriden. *Archiv für Protistenkunde* 58, 173–184 (in German).
- Kamptner, E., 1944. Coccolithineen-Studien in Golf von Neapel. *Wiener Botanische Zeitschrift* 93, 138–147 (in German).
- Kamptner, E., 1955. Fossile Coccolithineen-Skelettreste aus Insulinde. Eine mikropaläontologische Untersuchung. *Verhandelingen der Koninklijke Nederlandse Akademie van Wetenschappen, Afdeling Natuurkunde, Tweede Reeks* 50, 1–106 (in Dutch).
- Kamptner, E., 1963. Coccolithineen-Skelettreste aus Tiefseeablagerungen des Pazifischen Ozeans. *Annalen des Naturhistorischen Museums, Wien* 66, 139–204 (in German).
- Karabeyoğlu, A.U., Özkan-Altın, S., Altın, D., 2019. Quantitative analysis of planktonic foraminifera across the Cretaceous–Paleogene transition and observations on the extinction horizon, Haymana Basin, Turkey. *Cretaceous Research* 104, 104169.
- Karwath, B., Janofske, D., Tietjen, F., Willems, H., 2000. Temperature effects on growth and cell size in the marine calcareous dinoflagellate *Thoracospaera heimii*. *Marine Micropaleontology* 39, 43–51.
- Kasem, A.M., Wise Jr., S., Faris, M., Farouk, S., Zahran, E., 2017. Calcareous nannofossil biostratigraphy of the uppermost Maastrichtian–lower Paleocene at the Misheiti section, east central Sinai, Egypt. *Revue de Micropaléontologie* 60, 179–192.
- Katnick, D.C., Mustard, P.S., 2003. Geology of Denman and Hornby islands, British Columbia: implications for Nanaimo Basin evolution and formal definition of the Geoffrey and Spray formations, Upper Cretaceous Nanaimo Group. *Canadian Journal of Earth Sciences* 40, 375–393.
- Kaya Ozer, C., 2014. Calcareous nannofossil assemblage changes and stable isotope data from Maastrichtian to Selandian in the Akveren Formation, Western Black Sea, Turkey. *Arabian Journal of Geosciences* 7, 1233–1247.
- Keller, G., 1989. Extended Cretaceous/Tertiary boundary extinctions and delayed population change in planktonic foraminifera from Brazos River, Texas. *Paleoceanography* 4, 287–332.

- Keller, G., Sahni, A., Bajpai, S., 2009. Deccan volcanism, the K–T mass extinction and dinosaurs. *Journal of Biosciences* 34, 709–728.
- Keller, G., Barrera, E., Schmitz, B., Mattson, E., 1993. Gradual mass extinction, species survivorship, and long-term environmental changes across the Cretaceous-Tertiary boundary in high latitudes. *Geological Society of America Bulletin* 105, 979–997.
- Keller, G., Adatte, T., Stinnesbeck, W., Stüben, D., Berner, Z., 2001. Age, chemo- and biostratigraphy of Haiti spherule-rich deposits: A multi-event K–T scenario. *Canadian Journal of Earth Sciences* 38, 197–227.
- Kharajiany, S.O.A., Al-Qayim, B.A., Wise Jr., S.W., 2019. Calcareous nannofossil stratigraphy of the Upper Cretaceous–lower Paleocene sequence from the Chinarak section, Sulaimaniah area, Kurdistan Region, NE Iraq. *Iraqi Bulletin of Geology and Mining* 15, 1–14.
- Kharajiany, S.O.A., Wise Jr., S.W., Al-Qayim, B.A., 2020. The Danian sediments and the K/Pg boundary determination using calcareous nannofossil from Sulaimani area, Kurdistan Region/Iraq. *Carbonates and Evaporites* 35, 82.
- Khozyem, H., Tantawy, A.A., Mahmoud, A., Emam, A., Adatte, T., 2019. Biostratigraphy and geochemistry of the Cretaceous–Paleogene (K/Pg) and early Danian event (Dan-C2), a possible link to Deccan volcanism: New insights from Red Sea, Egypt. *Journal of African Earth Sciences* 160, 103645.
- Kienel, U., 1994. Die Entwicklung der kalkigen Nannofossilien und der kalkigen Dinoflagellaten-Zysten an der Kreide/Tertiär- Grenze in Westbrandenburg im Vergleich mit Profilen in Nordjütland und Seeland (Dänemark). *Berliner Geowissenschaftliche Abhandlungen, Reihe E, Paläobiologie* 12, 1–87, pl.1–15 (in German).
- Kiessling, W., Claeys, P., 2002. A geographic database approach to the KT boundary. In: Buffetaut, E., Koeberl, C. (Eds.), *Geological and biological effects of impact events. Impact studies*. Springer, Berlin, Heidelberg, pp. 83–140.
- Kirsch, K.-H., 1991. Dinoflagellatenzysten aus der Oberkreide des Helvetikums und Nordultrahelvetikums von Oberbayern. *Münchner Geowissenschaftliche Abhandlungen, Reihe A, Geologie und Paläontologie* 22, 1–306.
- Kilby, W.E., Wrightson, C.B., 1987. Bullmoose mapping and compilation project (93P/3, 4). British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork, 1986, Paper 1987,1 373–378.
- King, C., Iakovleva, A., Heilmann-Clausen, C., Steurbaut, E., 2018. Ypresian (early Eocene) stratigraphy of the Suvlu-Kaya reference section in the Bakhchisaray area (Crimea). *Newsletters on Stratigraphy* 51, 167–208.
- Kofoed, C.A., 1907a. The plates of *Ceratium* with a note on the unity of the genus. *Zoologischer*

Anzeiger 32, 177–183.

Kofoed, C.A., 1907b. Dinoflagellata of the San Diego region, III. Descriptions of new species. University of California, Publications in Zoology 3, 299–340, pls. 22–33.

Kofoed, C.A., 1909. On *Peridinium steini* Jörgensen, with a note on the nomenclature of the skeleton of the Peridinidae. Archiv für Protistenkunde 16, 25–47, 1 pl.

Kofoed, C.A., 1911. Dinoflagellata of the San Diego region, IV. The genus *Gonyaulax*, with notes on its skeletal morphology and a discussion of its generic and specific characters. University of California, Publications in Zoology 8, 187–286, pls. 9–17.

Kohring, R., 1993. Kalkdinoflagellaten aus dem Mittel- und Obereozän von Jütland (Dänemark) und dem Pariser Becken (Frankreich) im Vergleich mit anderen Tertiär-Vorkommen, Berliner Geowissenschaftliche Abhandlungen, Reihe E, Paläobiologie 6, 1–164, pls. 1–43 (in German).

Kohring, R., Gottschling, M., Keupp, H., 2005. Examples for character traits and palaeoecological significance of calcareous dinoflagellates. Paläontologische Zeitschrift 79, 79–91.

Kokinos, J.P., Anderson, D.M., 1995. Morphological development of resting cysts in cultures of the marine dinoflagellate *Lingulodinium polyedrum* (= *L. machaerophorum*). Palynology 19, 143–166.

Korbar, T., McDonald, I., Premec Fuček, V., Fuček, L., Posilović, H., 2017. Post-impact event bed (tsunamite) at the Cretaceous–Palaeogene boundary deposited on a distal carbonate platform interior. Terra Nova 29, 135–143.

Köthe, A., 1991. Paleogene dinoflagellates from northwest Germany; biostratigraphy and paleoenvironment. Geologisches Jahrbuch, Reihe A 118, 3–111.

Kouli, K., Brinkhuis, H., Dale, B., 2001. *Spiniferites cruciformis*: A fresh water dinoflagellate cyst? Review of Palaeobotany and Palynology 113, 273–286.

Koutsoukos, E.A.M., 2014. Phenotypic plasticity, speciation, and phylogeny in early Danian planktic foraminifera. Journal of Foraminiferal Research 44, 109–142.

Kurita, H., 2004. Paleogene dinoflagellate cyst biostratigraphy of northern Japan. Micropaleontology 50, 3–50.

Kurita, H., Obuse, A., 1994. Paleogene dinoflagellate cysts and pollen from the Haboro Formation, northern central Hokkaido, Japan, and their chronostratigraphic and paleoenvironmental implications. Journal of the Geological Society of Japan 100, 292–301 (in Japanese).

- Kurita, H., Obuse, A., 1997. Tertiary-Upper Cretaceous palynostratigraphy of the MITI Tempoku borehole, northern central Hokkaido. *Journal of Japanese Association of Petroleum Technology* 62, 13–24 (in Japanese).
- Kyte, F.T., Bostwick, J.A., Zhou, L., 1995. Identification and characterization of the Cretaceous/Tertiary boundary at ODP sites 886 and 803 and DSDP Site 576. In: Rea, D.K., Basov, I.A., Scholl, D.W., Allan, J.F. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results* 145, pp. 427–434.
- Laird, M.G., Bassett, K.N., Schiøler, P., Morgans, H.E.G., Bradshaw, J.D., Weaver, S.D., 2003. Paleoenvironmental and tectonic changes across the Cretaceous/Tertiary boundary at Tora, southeast Wairarapa, New Zealand: a link between Marlborough and Hawke's Bay. *New Zealand Journal of Geology and Geophysics* 46, 275–293.
- Lamolda, M.A., Melinte, M.C., Kaiho, K., 2005. Nannofloral extinction and survivorship across the K/T boundary at Caravaca, southeastern Spain. *Palaeogeography, Palaeoclimatology, Palaeoecology* 224, 27–52.
- Lamolda, M.A., Melinte-Dobrinescu, M.C., Kaiho, K., 2016. Calcareous nannoplankton assemblage changes linked to paleoenvironmental deterioration and recovery across the Cretaceous–Paleogene boundary in the Betic Cordillera (Agost, Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology* 441, 438–452.
- Landman, N.H., Johnson, R.O., Edwards, L.E., 2004a. Cephalopods from the Cretaceous/Tertiary boundary interval on the Atlantic Coastal Plain, with a description of the highest ammonite zones in North America. Part 1. Maryland and North Carolina. *American Museum Novitates* 3454, 1–64.
- Landman, N.H., Johnson, R.O., Edwards, L.E., 2004b. Cephalopods from the Cretaceous/Tertiary boundary interval on the Atlantic Coastal Plain, with a description of the highest ammonite zones in North America. Part 2. Northeastern Monmouth County, New Jersey. *Bulletin of the American Museum of Natural History* 287, 1–107.
- Landman, N.H., Johnson, R.O., Garb, M.P., Edwards, L.E., Kyte, F.T., 2007. Cephalopods from the Cretaceous/Tertiary boundary interval on the Atlantic Coastal Plain, with a description of the highest ammonite zones in North America. Part III. Manasquan River Basin, Monmouth County, New Jersey. *Bulletin of the American Museum of Natural History* 303, 1–122.
- Larina, E., Garb, M., Landman, N., Dastas, N., Thibault, N., Edwards, L., Phillips, G., Rovelli, R., Myers, C., Naujokaityte, J., 2016. Upper Maastrichtian ammonite biostratigraphy of the Gulf Coastal Plain (Mississippi Embayment, southern USA). *Cretaceous Research* 60, 128–151.
- Lebedeva, N.K., Kuzmina, O.B., Sobolev, E.S., Khazina, I. V., 2017. Stratigraphy of Upper Cretaceous and Cenozoic deposits of the Bakchar iron ore deposit (southwestern Siberia):

- New data. *Stratigraphy and Geological Correlation* 25, 76–98.
- Lejeune-Carpentier, M., Sarjeant, W.A.S., 1981. Restudy of some larger dinoflagellate cysts and an acritarch from the Upper Cretaceous of Belgium and Germany. *Annales de la Société Géologique de Belgique* 104, 1–39.
- Lentin, J.K., Vozzhennikova, T.F., 1990. Fossil dinoflagellates from the Jurassic, Cretaceous and Paleogene deposits of the USSR—a re-study. *American Association of Stratigraphic Palynologists, Contribution Series* 23, 221 pp.
- Lentin, J.K., Williams, G.L., 1976. A monograph of fossil peridinioid dinoflagellate cysts. *Bedford Institute of Oceanography, Report Series BI-R-75-16*, 237 pp.
- Lentin, J.K., Williams, G.L., 1980. Dinoflagellate provincialism with emphasis on Campanian peridiniaceans. *American Association of Stratigraphic Palynologists, Contributions Series* 7, 47 pp.
- Lentin, J.K., Williams, G.L., 1987. Status of the fossil dinoflagellate genera *Ceratiopsis* Vozzhennikova 1963 and *Cerodinium* Vozzhennikova 1963 emend. *Palynology* 11, 113–116.
- Lentin, J.K., Williams, G.L., 1993. Fossil dinoflagellates: index to genera and species 1993 edition. *American Association of Stratigraphic Palynologists, Contribution Series* 28, 856 + viii pp.
- Lentin, J.K., Williams, G.L., 1989. Fossil dinoflagellates: index to genera and species 1989 edition. *American Association of Stratigraphic Palynologists, Contributions Series* 20, 473 pp.
- Lessard, E.J., Swift, E., 1986. Dinoflagellates from the North Atlantic classified as phototrophic or heterotrophic by epifluorescence microscopy. *Journal of Plankton Research* 8, 1209–1215.
- Levy, R.H., Harwood, D.M., 2000. Tertiary marine palynomorphs from the McMurdo Sound erratics, Antarctica. In: Stilwell, J.D., Feldmann, R.M. (Eds.), *Paleobiology and paleoenvironments of Eocene rocks, McMurdo Sound, East Antarctica*. *Antarctic Research Series*, volume 76. American Geophysical Union, Washington (DC), pp. 183–242.
- Lewis, J., Hallett, R., 1997. *Lingulodinium polyedrum* (*Gonyaulax polyedra*), a blooming dinoflagellate. In: Ansell, A.D., Gibson, R.N., Barnes, M. (Eds.), *Oceanography and marine biology: An annual review* 35. UCL Press, London, pp. 97–161.
- Lewis, J., Dodge, J.D., Powell, A.J., 1990. Quaternary dinoflagellate cysts from the upwelling system offshore Peru, Hole 686B, ODP leg 112. In: Suess, E., von Huene, R. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results* 112, pp. 323–328.

- Lewis, J., Rochon, A., Harding, I., 1999. Preliminary observations of cyst-theca relationships in *Spiniferites ramosus* and *Spiniferites membranaceus* (Dinophyceae). *Grana* 38, 113–124.
- Li, L., Keller, G., 1999. Variability in Late Cretaceous climate and deep waters: Evidence from stable isotopes. *Marine Geology* 161, 171–190.
- Li, P., Kneller, B., Thompson, P., Bozetti, G., dos Santos, T., 2018. Architectural and facies organisation of slope channel fills: Upper Cretaceous Rosario Formation, Baja California, Mexico. *Marine and Petroleum Geology* 92, 632–649.
- Liengjarern, M., Costa, L., Downie, C., 1980. Dinoflagellate cysts from the upper Eocene–lower Oligocene of the Isle of Wight. *Palaeontology* 23, 475–499.
- Lindemann, E., 1928. Abteilung Peridineae (Dinoflagellatae). In: Engler, A., Prantl, K. (Eds.), *Die natürlichen Pflanzenfamilien nebst ihren Gattungen und wichtigeren Arten insbesondere den Nutzpflanzen. Band 2. Zweite stark vermehrte und verbesserte Auflage herausgegeben von A. Engler. Wilhelm Engelmann, Leipzig*, pp. 3–104 (in German).
- Lindgren, S., 1984. Acid resistant peridinioid dinoflagellates from the Maastrichtian of Trelleborg, southern Sweden. *Stockholm Contributions in Geology* 39, 145–201.
- Loeblich Jr., A.R., Loeblich III, A.R., 1969. Index to the genera, subgenera, and sections of the Pyrrhophyta, III. *Journal of Paleontology* 43, 193–198.
- Lohmann, H., 1920. Die Bevölkerung des Ozeans mit Plankton nach den Ergebnissen der Zentrifugenfänge während der Ausreise der Deutschland 1911, zugleich ein Beitrag zur Biologie des Atlantischen Ozeans. *Archiv für Biontologie* 4, 1–617 (in German).
- Londeix, L., Zonneveld, K., Masure, E., 2018. Taxonomy and operational identification of Quaternary species of *Spiniferites* and related genera. *Palynology* 42, 45–71.
- Lou, C., Jiang, C., Yang, M., Chen, M., Xiang, R., Zhang, L., Liu, J., Pan, A., 2016. Transportation modes of pollen in surface waters in the South China Sea and their environmental significance. *Review of Palaeobotany and Palynology* 225, 95–105.
- Ludvigsen, R., Beard, G., 1994. *West Coast fossils: A guide to the ancient life of Vancouver Island*. Whitecap Books, Vancouver, 194 pp.
- Ludvigsen, R., Beard, G., 1998. *West Coast fossils: A guide to the ancient life of Vancouver Island*, 2nd edition. Harbour Publishing, Madeira Park, British Columbia, 216 pp.
- Lund, J.J., Lund-Christensen, J., Strauss, C., 1993. Dinoflagellate cyst biostratigraphy and paleoenvironmental analysis in the Miocene of the RCNNS research well Nieder Ochtenhausen, NW Germany. In: Daber, R. (Ed.), *Festschrift Prof. W. Krutzsch. Museum für Naturkunde Berlin, Berlin*, pp. 27–37.

- Luterbacher, H.P., Ali, J.R., Brinkhuis, H., Gradstein, F.M., Hooker, J.J., Monechi, S., Ogg, J.G., Powell, J., Röhl, U., Sanfilippo, A., Schmitz, B., 2004. The Paleogene Period. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.). *A geologic time scale 2004*. Cambridge University Press, Cambridge, pp. 384–408.
- M’Hamdi, A., Slimani, H., Ismail-Lattrache, K.B., Soussi, M., 2013. Biostratigraphie des kystes de dinoflagellés de la limite Crétacé-Paléogène à Ellès, Tunisie. *Revue de Micropaleontologie* 56, 27–42 (in French).
- M’Hamdi, A., Slimani, H., Louwye, S., Soussi, M., Ismail-Lattrache, K.B., Ali, W.B., 2015. Les kystes de dinoflagelles et palynofacies de la transition Maastrichtien–Danien du stratotype El kef (Tunisie). *Comptes Rendus Palevol* 14, 167–180 (in French).
- MacLeod, K.G., Whitney, D.L., Huber, B.T., Koeberl, C., 2007. Impact and extinction in remarkably complete Cretaceous-Tertiary boundary sections from Demerara Rise, tropical western North Atlantic. *Geological Society of America, Bulletin* 119, 101–115.
- Macleod, N., Rawson, P.F., Forey, P.L., Banner, F.T., Boudagher-Fadel, M.K., Bown, P.R., Burnett, J.A., Chambers, P., Culver, S., Evans, S.E., Jeffery, C., Kaminski, M.A., Lord, A.R., Milner, A.C., Milner, A.R., Morris, N., Owen, E., Rosen, B.R., Smith, A.B., Taylor, P.D., Urquhart, E., Young, J.R. 1997. The Cretaceous–Tertiary biotic transition. *Journal of the Geological Society, London* 154, 265–292.
- Mahanipour, A., Parandavar, M., Youssef, M., 2021. Calcareous nannofossil biostratigraphy of the Late Cretaceous–early Paleocene interval in the Zagros Basin (southeastern Tethys), Iran. *Alcheringa*, 1872704.
- Mao, S. 1989. Dinoflagellata. In: Yichun, H., Mao, S., Peihua, R., Xin, S., Sheping, S., Wang, Z., Jiayun, Y., Zheng, H. (Eds.), *Quaternary microbiotas and their geological significance from northern Xisha Trench of South China Sea*. China University of Geosciences Press, Wuhan, China, pp. 132–218 (in Chinese).
- Mao, S., Mohr, B.A.R., 1992. Late Cretaceous dinoflagellate cysts (?Santonian–Maestrichtian) from the southern Indian Ocean (Hole 748C). In: Wise Jr., S.W., Palmer Julson, A.A., Schlich, R., Thomas, E. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results* 120, College Station, Texas, pp. 307–341.
- Mao, S., Norris, G., 1988. Late Cretaceous–early Tertiary dinoflagellates and acritarchs from the Kashi area, Tarim Basin, Xinjiang Province, China. *Contributions of the Royal Ontario Museum, Life Sciences Division* 150, 1–93.
- Mao, S., Hardland, R., 1993. Quaternary organic-walled dinoflagellate cysts from the South China Sea and their paleoclimatic significance. *Palynology* 17, 47–65.
- Machalski, M., Vellekoop, J., Dubicka, Z., Peryt, D., Harasimiuk, M., 2016. Late Maastrichtian cephalopods, dinoflagellate cysts and foraminifera from the Cretaceous–Paleogene

- succession at Lechówka, southeast Poland: stratigraphic and environmental implications. *Cretaceous Research* 57, 208–227.
- MacLaurin, C.I., Mahoney, J.B., Haggart, J.W., Goodin, J.R., Mustard, P.S., 2011. The Jackass Mountain Group of south-central British Columbia: depositional setting and evolution of an Early Cretaceous deltaic complex. *Canadian Journal of Earth Sciences* 48, 930–951.
- Mahboub, I., Slimani, H., Toufiq, A., Chekar, M., Djeya, K.L., Jbari, H., Chakir, S., 2019. Middle Eocene to early Oligocene dinoflagellate cyst biostratigraphy and paleoenvironmental interpretations of the Ben Attaya section at Taza, eastern External Rif, Morocco. *Journal of African Earth Sciences* 149, 154–169.
- Mantell, G.A., 1854. The medals of creation; or, first lessons in geology and the study of organic remains, 2nd ed. Henry G. Bohn, London, 930 pp., pls. 1–6 (in two volumes).
- Marheinecke, U., 1992. Monographie der Dinozysten, Acritarcha und Chlorophyta des Maastrichtium von Hemmoor (Niedersachsen). *Palaeontographica, Abteilung B* 227, 1–173, 30 pls. (in German).
- Marincovich Jr., L., 1993. Danian mollusks from the Prince Creek Formation, northern Alaska, and implications for Arctic Ocean paleogeography. *Memoirs of The Paleontological Society* 35, 1–35.
- Mariotti, A., Gadel, F., Giresse, P., Kinga-Mouzeo, 1991. Carbon isotope composition and geochemistry of particulate organic matter in the Congo River (central Africa): Application to the study of Quaternary sediments off the mouth of the river. *Chemical Geology: Isotope Geoscience Section* 86, 345–357.
- Marret, F., de Vernal, A., Pedersen, T.F., McDonald, D., 2001a. Middle Pleistocene to Holocene palynostratigraphy of Ocean Drilling Program Site 887 in the Gulf of Alaska, northeastern North Pacific. *Canadian Journal of Earth Sciences* 38, 373–386.
- Marret, F., de Vernal, A., Benderra, F., Harland, R., 2001b. Late Quaternary sea-surface conditions at DSDP Hole 594 in the southwest Pacific Ocean based on dinoflagellate cyst assemblages. *Journal of Quaternary Science* 16, 739–751.
- Marret, F., Zonneveld, K.A.F., 2003. Atlas of modern organic-walled dinoflagellate cyst distribution. *Review of Palaeobotany and Palynology* 125, 1–200.
- Mathewes, R.W., Greenwood, D.R., Love, R.L., 2020. The Kanaka Creek fossil flora (Huntingdon Formation), British Columbia, Canada—paleoenvironment and evidence for Paleocene age using palynology and macroflora. *Canadian Journal of Earth Sciences* 57, 348–365.
- Matsumoto, T., 1960. Upper Cretaceous ammonites of California. Part III: With notes on stratigraphy of the Redding area and the Santa Ana Mountains. *Memoirs, Faculty of*

Science Kyushu University, Series D. Geology, Special Volume 11, 204 pp.

- Matthews, W.A., Guest, B., Coutts, D., Bain, H., Hubbard, S., 2017. Detrital zircons from the Nanaimo basin, Vancouver Island, British Columbia: An independent test of Late Cretaceous to Cenozoic northward translation. *Tectonics* 36, 854–876.
- Matthiessen, J., Knies, J., Nowaczyk, N.R., Stein, R., 2001. Late Quaternary dinoflagellate cyst stratigraphy at the Eurasian continental margin, Arctic Ocean: indications for Atlantic water inflow in the past 150,000 years. *Global and Planetary Change* 31, 65–86.
- May, F.E., 1980. Dinoflagellate cysts of the Gymnodiniaceae, Peridiniaceae, and Gonyaulacaceae from the Upper Cretaceous Monmouth Group, Atlantic Highlands, New Jersey. *Palaeontographica, Abteilung B* 172, 10–116, 23 pls.
- McCarthy, F.M.G., Mudie, P.J., 1996. Palynology and dinoflagellate biostratigraphy of upper Cenozoic sediments from sites 898 and 900, Iberia Abyssal Plain. In: Whitmarsh, R.B., Sawyer, D.S., Klaus, A., Masson, D.G. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results* 149, College Station, Texas, pp. 241–265.
- McCarthy, F.M.G., Mudie, P.J., 1998. Oceanic pollen transport and pollen: Dinocyst ratios as markers of late Cenozoic sea level change and sediment transport. *Palaeogeography, Palaeoclimatology, Palaeoecology* 138, 187–206.
- McCarthy, F.M.G., Gostlin, K.E., Mudie, P.J., Hopkins, J.A., 2003. Terrestrial and marine palynomorphs as sea-level proxies; an example from Quaternary sediments on the New Jersey margin, U.S.A. *Society of Economic Paleontologists and Mineralogists Special Publication* 75, 19–129.
- McCrea, R.T., Buckley, L.G., Plint, A.G., Lockley, M.G., Matthews, N.A., Noble, T.A., Xing, L., Krawetz, J.R., 2015. Vertebrate ichnites from the Boulder Creek Formation (Lower Cretaceous: middle to ? upper Albian) of northeastern British Columbia, with a description of a new avian ichnotaxon, *Paxavipes babcockensis* ichnogen. et isp. nov. *Cretaceous Research* 55, 1–18.
- McGugan, A., 1962. Upper Cretaceous foraminiferal zones, Vancouver Island, British Columbia, Canada. *Journal of the Alberta Society of Petroleum Geologists* 10, 585–592.
- McGugan, A., 1964. Upper Cretaceous zone Foraminifera, Vancouver Island, British Columbia, Canada. *Journal of Paleontology* 38, 933–951, pls. 150–152.
- McGugan, A., 1979. Biostratigraphy and paleoecology of Upper Cretaceous (Campanian and Maestrichtian) Foraminifera from the upper Lambert, Northumberland, and Spray formations, Gulf Islands, British Columbia. *Canadian Journal of Earth Sciences* 16, 2263–2274.
- McGugan, A., 1982. Upper Cretaceous (Campanian and Maestrichtian) foraminifera from the

- upper Lambert and Northumberland formations, Gulf Islands, British Columbia, Canada. *Micropaleontology* 28, 399–430.
- McIntyre, J.D., 1999. Campanian to Paleocene dinoflagellate assemblages from the Turtle Mountain core hole, Manitoba, western Canada. *Canadian Journal of Earth Sciences* 36, 769–774.
- McLachlan, S.M.S., Haggart, J.W., 2018. Reassessment of the late Campanian (Late Cretaceous) heteromorph ammonite fauna from Hornby Island, British Columbia, with implications for the taxonomy of the Diplomoceratidae and Nostoceratidae. *Journal of Systematic Palaeontology* 16, 1247–1299.
- McLachlan, S.M.S., Pospelova, V., 2021. Dinoflagellate cyst-based paleoenvironmental reconstructions and phytoplankton paleoecology across the Cretaceous–Paleogene (K/Pg) boundary interval, Vancouver Island, British Columbia, Canada. *Cretaceous Research* 126, 104878.
- McLachlan, S.M.S., Pospelova, V., Hebda, R.J., 2018. Dinoflagellate cysts from the upper Campanian (Upper Cretaceous) of Hornby Island, British Columbia, Canada, with implications for Nanaimo Group biostratigraphy and paleoenvironmental reconstructions. *Marine Micropaleontology* 145, 1–20.
- McLachlan, S.M.S., Pospelova, V., Hebda, R.J., 2019. Areoligeracean dinoflagellate cysts from the upper Campanian (Upper Cretaceous) of Hornby Island, British Columbia, Canada. *Palynology* 43, 669–689.
- McLachlan, S.M.S., Pospelova, V., Humphrey, E.C., 2021. Vesiculation in the dinoflagellate cyst *Cannosphaeropsis franciscana* Damassa, 1979 across the K/Pg boundary (Vancouver Island, Canada) with implications for spiniferate gonyaulacacean taxonomy and ecophenotypy. *Review of Palaeobotany and Palynology* 292, 104452.
- McLean, D.M., 1973. Emendation and transfer of *Eisenackia* (Pyrrhophyta) from the Microdiniaceae to the Gonyaulacaceae. *Geologiska Föreningens i Stockholm Förhandlingar* 95, 261–265.
- Meier, K.J.S., Janofske, D., Willems, H., 2002. New calcareous dinoflagellates (Calciodinelloideae) from the Mediterranean Sea. *Journal of Phycology* 38, 602–615.
- Meltsov, V., Poska, A., Saar, M., 2008. Pollen size in *Carex*: The effect of different chemical treatments and mounting media. *Grana* 47, 220–233.
- Mertens, K.N., Carbonell-Moore, C., 2018. Introduction to *Spiniferites* Mantell 1850 special issue. *Palynology* 42, 1–9.
- Mertens, K.N., Price, A.M., Pospelova, V., 2012c. Determining the absolute abundance of dinoflagellate cysts in recent marine sediments II: Further tests of the *Lycopodium* marker-

- grain method. Review of Palaeobotany and Palynology 184, 74–81.
- Mertens, K.N., Dale, B., Ellegaard, M., Jansson, I.-M., Godhe, A., Kremp, A., Louwye, S., 2011. Process length variation in cysts of the dinoflagellate *Protoceratium reticulatum*, from surface sediments of the Baltic–Kattegat–Skagerrak estuarine system: a regional salinity proxy. Boreas 40, 242–255.
- Mertens, K.N., Bradley, L.R., Takano, Y., Mudie, P.J., Marret, F., Aksu, A.E., Hiscott, R.N., Verleye, T.J., Mousing, E.A., Smyrnova, L.L., Bagheri, S., Mansor, M., Pospelova, V., Matsuoka, K., 2012a. Quantitative estimation of Holocene surface salinity variation in the Black Sea using dinoflagellate cyst process length. Quaternary Science Reviews 39, 45–59.
- Mertens, K.N., Bringué, M., Van Nieuwenhove, N., Takano, Y., Pospelova, V., Rochon, A., de Vernal, A., Radi, T., Dale, B., Patterson, R.T., Weckström, K., Andrén, E., Louwye, S. and Matsuoka, K. 2012b. Process length variation of the cyst of the dinoflagellate *Protoceratium reticulatum* in the North Pacific and Baltic-Skagerrak region: calibration as annual density proxy and first evidence of pseudo-cryptic speciation. Journal of Quaternary Science 27, 734–744.
- Mertens, K.N., Ribeiro, S., Bouimetarhan, I., Caner, H., Combourieu-Nebout, N., Dale, B., de Vernal, A., Ellegaard, M., Filipova, M., Godhe, A., Goubert, E., Grøsfjeld, K., Holzwarth, U., Kotthoff, U., Leroy, S.A.G., Londeix, L., Marret, F., Matsuoka, K., Mudie, P.J., Naudts, L., Peña-Manjarrez, J.L., Persson, A., Popescu, S.-M., Pospelova, V., Sangiorgi, F., van der Meer, M.T.J., Vink, A., Zonneveld, K.A.F., Vercauteren, D., Vlassenbroeck, J., Louwye, S., 2009a. Process length variation in cysts of a dinoflagellate, *Lingulodinium machaerophorum*, in surface sediments: Investigating its potential as salinity proxy. Marine Micropaleontology 70, 54–69.
- Mertens, K.N., Van Nieuwenhove, N., Gurdebeke, P.R., Aydin, H., Bogus, K., Bringué, M., Dale, B., De Schepper, S., de Vernal, A., Ellegaard, M., Grothe, A., Haifeng Gu, Head, M.J., Heikkilä, M., Limoges, A., Londeix, L., Louwye, S., Marret, F., Masure, E., Matsuoka, K., Mudie, P.J., Penaud, A., Pospelova, V., Price, A.M., Ribeiro, S., Rochon, A., Sangiorgi, F., Schreck, M., Torres, V., Uzar, S., Versteegh, G.J.M., Warny, S., Zonneveld, K., 2018. The dinoflagellate cyst genera *Achomosphaera* Evitt 1963 and *Spiniferites* Mantell 1850 in Pliocene to modern sediments: a summary of round table discussions. Palynology 42, 10–44.
- Mertens, K.N., Verhoeven, K., Verleye, T., Louwye, S., Amorim, A., Ribeiro, S., Deaf, A.S., Harding, I.C., De Schepper, S., González, C., Kodrans-Nsiah, M., de Vernal, A., Henry, M., Radi, T., Dybkjaer, K., Poulsen, N.E., Feist-Burkhardt, S., Chitolie, J., Heilmann-Clausen, C., Londeix, L., Turon, J.-L., Marret, F., Matthiessen, J., McCarthy, F.M.G., Prasad, V., Pospelova, V., Kyffin Hughes, J.E., Riding, J.B., Rochon, A., Sangiorgi, F., Welters, N., Sinclair, N., Thun, C., Soliman, A., Van Nieuwenhove, N., Vink, A., Young, M., 2009b. Determining the absolute abundance of dinoflagellate cysts in recent marine sediments: The *Lycopodium* marker-grain method put to the test. Review of Palaeobotany and Palynology 157, 238–252.

- Michel, H.V., Asaro, F., Alvarez, W., Alvarez, L.W., 1985. Elemental profile of iridium and other elements near the Cretaceous/Tertiary boundary in Hole 577B. Deep Sea Drilling Project, Initial Reports 86, 533–538.
- Miller, K.G., 2009. Sea level change, last 250 million years. In: Gornitz, V. (Ed.), Encyclopedia of paleoclimatology and ancient environments, Encyclopedia of Earth Sciences Series. Springer, Dordrecht, pp. 879–887.
- Miller, K.G., Sherrell, R.M., Browning, J.V., Field, M.P., Gallagher, W., Olsson, R.K., Sugarman, P.J., Tuorto, S., Wahyudi, H., 2010. Relationship between mass extinction and iridium across the Cretaceous-Paleogene boundary in New Jersey. *Geology* 38, 867–870.
- Miller, R.B., Gordon, S.M., Bowring, S.A., Doran, B.A., McLean, N.M., Michels, Z.D., Shea, E.K., Whitney, D.L., Wintzer, N.E., Mendoza, M.K., 2009. Linking deep and shallow crustal processes in an exhumed continental arc, North Cascades, Washington. In: O'Connor, J.E., Dorsey, R.J., Madin, I.P. (Eds.), *Volcanoes to vineyards: Geologic field trips through the dynamic landscape of the Pacific Northwest*. Geological Society of America Field Guide 15, pp. 373–406.
- Mindell, R.A., Stockey, R.A., Beard, G., 2006a. Anatomically preserved staminate inflorescences of *Gynoplatananthus oysterbayensis* gen. et sp. nov. (Platanaceae) and associated pistillate fructifications from the Eocene of Vancouver Island, British Columbia. *International Journal of Plant Sciences* 167, 591–600.
- Mindell, R.A., Stockey, R.A., Beard, G., 2007a. *Cascadiacarpa spinosa* gen. et sp. nov. (Fagaceae): Castaneoid fruits from the Eocene of Vancouver Island, Canada. *American Journal of Botany* 94, 351–361.
- Mindell, R.A., Stockey, R.A., Beard, G., 2009. Permineralized *Fagus* nuts from the Eocene of Vancouver Island, Canada. *International Journal of Plant Sciences* 170, 551–560.
- Mindell, R.A., Stockey, R.A., Beard, G., 2014. *Cascadiacarpa exilis* sp. nov.: new fruits of Fagaceae from the Eocene of British Columbia. *Botany* 92, 377–387.
- Mindell, R.A., Rothwell, G.W., Beard, G., Stockey, Ruth, A., 2006b. *Gleichenia appianensis* sp. nov. (Gleicheniaceae): a permineralized rhizome and associated vegetative remains from the Eocene of Vancouver Island, British Columbia. *International Journal of Plant Sciences* 167, 639–647.
- Mindell, R.A., Stockey, R.A., Beard, G., Currah, R.S., 2007b. *Margaretbarromyces dictyosporus* gen. sp. nov.: a permineralized corticolous ascomycete from the Eocene of Vancouver Island, British Columbia. *Mycological Research* 111, 680–684.
- Mita, H., Shimoyama, A., 1999. Distribution of polycyclic aromatic hydrocarbons in the K/T boundary sediments at Kwaruppu, Hokkaido, Japan. *Geochemical Journal* 33, 305–316.

- Mohamed, O., Wagreich, M., 2013. Organic-walled dinoflagellate cyst biostratigraphy of the Well Höflein 6 in the Cretaceous–Paleogene Rhenodanubian Flysch Zone (Vienna Basin, Austria). *Geological Carpathica* 64, 209–230.
- Mohamed, O., Piller, W.E., Egger, H., 2012. The dinocyst record across the Cretaceous/Palaeogene boundary of a bathyal mid-latitude Tethyan setting: Gosau Group, Gams Basin, Austria. *Cretaceous Research* 35, 143–168.
- Mohamed, O., Piller, W.E., Egger, H., 2013. Dinoflagellate cysts and palynofacies across the Cretaceous/Palaeogene boundary at the neritic Waidach Section (Eastern Alps, Austria). *Review of Palaeobotany Palynology* 190, 85–103.
- Molina, E., Alegret, L., Arenillas, I., Arz, J.A., Gallala, N., Grajales-Nishimura, J.M., Murillo-Muñetón, G., Zaghib-Turki, D., 2009. The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, “Tertiary”, Cenozoic): auxiliary sections and correlation. *Episodes* 32, 84–95.
- Molina, E., Alegret, L., Arenilla, I., Arz, J.A., Gallala, N., Hardenbol, J., Von Salis, K., Steurbaut, E., Vandenbelghe, N., Zaghib-Turki, D., 2006. The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, “Tertiary”, Cenozoic) at El Kef, Tunisia—original definition and revision. *Episodes* 29, 263–273.
- Monechi, S., 1985. Campanian to Pleistocene calcareous nannofossil stratigraphy from northwest Pacific Ocean, Deep Sea Drilling Project Leg 86. *Deep Sea Drilling Project, Initial Reports* 86, 301–336.
- Monechi, S., Bleil, U., Backman, J., 1985. Magnetobiochronology of Late Cretaceous–Paleogene and Late Cenozoic Pelagic sedimentary sequences from the northwest Pacific (Deep Sea Drilling Project, Leg 86, Site 577). *Deep Sea Drilling Project, Initial Reports* 86, 787–797.
- Monger, J.W.H., Journeay, J.M. 1994. Guide to the geology and tectonic evolution of the southern Coast Mountains. Geological Survey of Canada, Open File 2490, 77 pp.
- Montanari, A., Hay, R.L., Alvarez, W., Asaro, F., Michel, H.V., Alvarez, L.W., Smit, J., 1983. Spheroids at the Cretaceous-Tertiary boundary are altered impact droplets of basaltic composition. *Geology* 11, 668–671.
- Monteil, E., 1990. Revision and emendation of dinocyst genus *Amphorula* Dodekova 1969 . The concept of morphostratigraphy. *Bulletin Centres Recherche Exploration–Production Elf-Aquitaine* 14, 597–609.
- Monteil, E., 2005. Morphostratigraphy: a new non-taxonomic biostratigraphical technique applied to a turbiditic deep-sea reservoir (Paleocene Maureen Formation, Fleming Field, UKCS). In: Powell, A. J., Riding, J.B. (Eds.), *Recent developments in applied biostratigraphy*. The Micropalaeontological Society, Special Publications, pp. 5–21.

- Mort, A.P., Adatte, T., Föllmi, K.B., Keller, G., Steinmann, P., Virginie, M., Berner, Z., Stuben, D., 2007. Phosphorus and the roles of productivity and nutrient recycling during Oceanic Anoxic Event 2. *Geology* 35, 483–486.
- Morton, A.C., Evans, D., Harland, R., King, C., Ritchie, D.K., 1988. Volcanic ash in a cored borehole W of the Shetland Islands: evidence for Selandian (late Palaeocene) volcanism in the Faeroes region. Geological Society, London, Special Publications 39, 263–269.
- Moshkovitz, S., Habib, D., 1993. Calcareous nannofossil and dinoflagellate stratigraphy of the Cretaceous-Tertiary Boundary Alabama and Georgia. *Micropaleontology* 39, 167–191.
- Mousing, E.A., Ribeiro, S., Chisholm, C., Kuijpers, A., Moros, M., Ellegaard, M., 2017. Size differences of Arctic marine protists between two climate periods—using the paleoecological record to assess the importance of within-species trait variation. *Ecology and Evolution* 7, 3–13.
- Mudie, P.J., Harland, R., 1996. Aquatic Quaternary, In: Jansonius, J., McGregor, D.C. (Eds.), *Palynology: principles and applications*, volume 3. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 843–877.
- Mudie, P.J., Aksu, A.E., Yasar, D., 2001. Late Quaternary dinoflagellate cysts from the Black, Marmara and Aegean seas: variations in assemblages, morphology and paleosalinity. *Marine Micropaleontology* 43, 155–178.
- Müller, C., 1972. Kalkiges Nannoplankton aus Tiefseekernen des Ionischen Meeres. “Meteor” Forschungsergebnisse, Reihe C, *Geologie und Geophysik* 10, 75–95 (in German).
- Muller, J.E., Carson, D.J.T., 1969. Geology and mineral deposits of Alberni map-area, British Columbia (92F). Geological Survey of Canada, Paper 68-50, 1–52.
- Muller, J.E., Jeletzky, J.A., 1970. Geology of the Upper Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia. Geological Survey of Canada, Paper 69-25, 1–77.
- Muller, J.E., Cameron, B.E.B., Northcote, K.E., 1981. Geology and mineral deposits of Nootka Sound map-area Vancouver Island, British Columbia. Geological Survey of Canada, Paper 80-16, 1–53.
- Mustard, P.S., 1994. The Upper Cretaceous Nanaimo Group, Georgia Basin. Geological Survey of Canada, Bulletin 481, 27–95.
- Mustard, P.S., Rouse, G.E., 1991. Sedimentary outliers of the eastern Georgia Basin margin, British Columbia. Current Research, Part A, Geological Survey of Canada, Paper 91-1A, 229–240.

- Mustard, P.S., Rouse, G.E., 1992. Tertiary Georgia Basin, British Columbia and Washington State: a view from the other side. *Current Research, Part A, Geological Survey of Canada, Paper 92-1A*, 13–23.
- Mustard, P.S., Rouse, G.E., 1994. Stratigraphy and evolution of Tertiary Georgia Basin and subjacent Upper Cretaceous sedimentary rocks, southwestern British Columbia and northwestern Washington State. *Geological Survey of Canada, Bulletin 481*, 97–169.
- Mustard, P.S., Parrish, R.R., McNicoll, V., 1995. Provenance of the Upper Cretaceous Nanaimo Group, British Columbia: evidence from U-Pb analyses of detrital zircons. *Society of Economic Paleontologists and Mineralogists, Special Publication 52*, 65–76.
- Mustard, P., Haggart, J., Katnick, D., Treptau, K., MacEachern, J., 2003. Sedimentology, paleontology, ichnology and sequence stratigraphy of the Upper Cretaceous Nanaimo Group submarine fan deposits, Denman and Hornby islands, British Columbia. In: Woodsworth, J. (Ed.), *Guidebook for geological field trips in southern British Columbia*. Geological Association of Canada, Cordilleran Section, Vancouver, pp. 103–145.
- Mustoe, G.E., Beard, G., 2021. Calcite mineralized wood from Vancouver Island, British Columbia, Canada. *Geosciences* 11, 1–29.
- Mustoe, G.E., Gannaway, W.L., 1997. Paleogeography and paleontology of the early Tertiary Chuckanut Formation, northwest Washington. *Washington Geology* 25, 3–18.
- Mustoe, G.E., Dillhoff, R.H., Dillhoff, T.A., 2007. Geology and paleontology of the early Tertiary Chuckanut Formation. *Geological Society of America Field Guide* 9, 121–135.
- Naeher, S., Hollis, C.J., Clowes, C.D., Ventura, G.T., Shepherd, C.L., Crouch, E.M., Morgans, H.E.G., Bland, K.J., Strogon, D.P., Sykes, R., 2019. Depositional and organofacies influences on the petroleum potential of an unusual marine source rock: Waipawa Formation (Paleocene) in southern East Coast Basin, New Zealand. *Marine and Petroleum Geology* 104, 468–488.
- Nagy, J., Kaminski, M.A., Gradstein, F.M., Johnson, K., 2004. Quantitative foraminiferal and palynomorph biostratigraphy of the Paleogene in the southwestern Barents Sea. *Grzybowski Foundation, Special Publication 8*, 359–379.
- Nichols, D.J., Johnson, K.R., 2008. *Plants and the K–T boundary*. Cambridge University Press, Cambridge, 292 pp.
- Nøhr-Hansen, H., 1994. Dinoflagellate cyst biostratigraphy of the Upper Cretaceous black mudstones between Niaqornat and Ikorfat of the north coast of Nuussuaq West Greenland. *Grønlands Geologiske Undersøgelse, Open File Series 94/14*, 1–24.
- Nøhr-Hansen, H., Dam, G., 1997. Palynology and sedimentology across a new marine Cretaceous-Tertiary boundary section on Nuussuaq, West Greenland. *Geology* 25, 851–854.

- Nøhr-Hansen, H., Heilmann-Clausen, C., 2001. *Cerodinium kangiliense* n. sp. and *Senegalinium iterlaense* n. sp. — two new stratigraphically important Paleocene species from West Greenland and Denmark. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 219, 153–170.
- Nøhr-Hansen, H., Williams, G.L., Fensome, R.A., 2016. Biostratigraphic correlation of the western and eastern margins of the Labrador–Baffin Seaway and implications for the regional geology. *Geological Survey of Denmark and Greenland Bulletin* 37, 1–74.
- Nøhr-Hansen, H., Nielsen, L.H., Sheldon, E., Hovikoski, J., Alsen, P., 2011. Palaeogene deposits in north-east Greenland. *Geological Survey of Denmark and Greenland Bulletin* 23, 61–64.
- Norris, G., 1997. Paleocene-Pliocene deltaic to inner shelf palynostratigraphic zonation, depositional environments and paleoclimates in the Imperial Adgo F-28 well, Beaufort-Mackenzie Basin. *Geological Survey of Canada, Bulletin* 523, 1–71.
- Norris, G., Sarjeant, W.A.S., 1965. A descriptive index of genera of fossil Dinophyceae and Acritarcha. *New Zealand Geological Survey, Paleontological Bulletin* 40, 1–72.
- Nyborg, T.G., Garassino, A., De Angeli, A., Ross, R.L.M., 2015. A new squat lobster (Crustacea, Anomura, Munidopsidae) from the middle-late Eocene of British Columbia (Canada). *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 275, 357–361.
- Nyborg, T., McLachlan, S.M.S., Garassino, A., Vega, F.J., Phillippe, S.C., Champagne, D.E., 2019. New and revised species of *Archaeopus* RATHBUN, 1908 (Decapoda: Brachyura: Retroplumidae) from the eastern Pacific. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 292, 25–56.
- O’Leary, M.H., 1988. Carbon isotopes in photosynthesis. *Bioscience* 38, 328–336.
- Oboh-ikuenobe, F.E., Yepes, O., Gregg, J.M., 1998. Palynostratigraphy, palynofacies, and thermal maturation of Cretaceous–Paleocene sediments from the Côte D’Ivoire-Ghana Transform Margin. In: Mascle, J., Lohmann, G.P., Moullade, M. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results* 159, College Station, Texas, pp. 277–318.
- Oboh-Ikuenobe, F.E., Antolinez-Delgado, H., Awad, W.K., 2017. Dinoflagellate cyst assemblages, biostratigraphy and paleoenvironment of a Paleocene–early Eocene sedimentary succession in the northern Niger Delta Basin: Comparison with low, mid and high latitude regions. *Palaeogeography, Palaeoclimatology, Palaeoecology* 481, 29–43.
- Oboh-ikuenobe, F.E., Spencer, M.K., Campbell, C.E., Haselwander, R.D., 2012. A portrait of late Maastrichtian and Paleocene palynoflora and paleoenvironment in the northern Mississippi Embayment, southeastern Missouri. *Palynology* 36, 63–79.
- Officer, C.B., Lynch, D.R., 1983. Determination of mixing parameters from tracer distributions

- in deep-sea sediment cores. *Marine Geology* 52, 59–74.
- Officer, C.B., Drake, C.L., 1985. Terminal Cretaceous environmental events. *Science* 227, 1161–1167.
- Oloto, I.N., 1989. Maastrichtian dinoflagellate cyst assemblage from the Nkporo Shale on the Benin Flank of the Niger Delta. *Review of Palaeobotany and Palynology* 57, 173–186.
- Olsson, R.K., Miller, K.G., Browning, J. V, Wright, J.D., Cramer, B.S., 2002. Sequence stratigraphy and sea-level change across the Cretaceous-Tertiary boundary on the New Jersey passive margin. *Geological Society of America, Special Papers* 356, 97–108.
- Otero, E., Culp, R., Noakes, J.E., Hodson, R.E., 2000. Allocation of particulate organic carbon from different sources in two contrasting estuaries of southeastern U.S.A. *Limnology and Oceanography* 45, 1753–1763.
- Palynodata Inc., White, J.M., 2008. Palynodata Datafile: 2006 version with introduction by J.M. White. Geological Survey of Canada, Open File 5793.
- Pan Li, Kneller, B., Thompson, P., Bozetti, G., Dos Santos, T., 2018. Architectural and facies organisation of slope channel fills: Upper Cretaceous Rosario Formation, Baja California, Mexico. *Marine and Petroleum Geology* 92, 632–649.
- Parandavar, M., Mahanipur, A., Aghanabati, S.A., Hoseini, S.A., 2013. Calcareous nannofossil biostratigraphy of the upper part of Gurpi Formation–lower part of Pabdeh Formation (Purple Shale) at the north-east of Gurpi Anticline. *Journal of Geoscience* 89, 187–198 (in Persian).
- Pardo, A., Ortiz, N., Keller, G., 1996. Latest Maastrichtian and Cretaceous–Tertiary boundary foraminiferal turnover and environmental changes at Agost, Spain. In: MacLeod, N., Keller, G. (Eds.), *Cretaceous–Tertiary mass extinctions: biotic and environmental changes*. W.W. Norton and Co., London, pp. 139–171.
- Park, J-W., Zhaichu Hu, Han Gao, Campbell, I.H., Hujun Gong, 2012. Platinum group element abundances in the upper continental crust revisited—new constraints from analyses of Chinese loess. *Geochimica et Cosmochimica Acta* 93, 63–76.
- Parras, A., Guerslein, G.R., Pérez Panera, J.P., Griffin, M., Náñez, C., Cusminsky, G., Quiroga, A., 2020. Integrated stratigraphy and paleontology of the lower Miocene Monte León Formation, southeastern Patagonia, Argentina: Unraveling paleoenvironmental changes and factors controlling sedimentation. *Palaeogeography, Palaeoclimatology, Palaeoecology* 556, 109701.
- Pascher, A., 1914. Über Flagellaten und Algen. *Deutsche Botanische Gesellschaft, Berichte* 32, 136–160 (in German).

- Patterson, R.T., Haggart, J.W., Dalby, A.P., 2010. A guide to late Albian-Cenomanian (Cretaceous) Foraminifera from the Queen Charlotte Islands, British Columbia, Canada. *Palaeontologia Electronica* 13, 12A.
- Pearce, M.A., 2010. New organic-walled dinoflagellate cysts from the Cenomanian to Maastrichtian of the Trunch borehole, UK. *Journal of Micropalaeontology* 29, 51–72.
- Pearce, M.A., Jarvis, I., Tocher, B.A., 2009. The Cenomanian–Turonian boundary event, OAE2 and palaeoenvironmental change in epicontinental seas: New insights from the dinocyst and geochemical records. *Palaeogeography, Palaeoclimatology, Palaeoecology* 280, 207–234.
- Pearce, M.A., Stickley, C.E., Johansen, L.M., 2019. *Chatangiella islae* and *Trithyrodinium zakkii*, new species of peridinioid dinoflagellate cysts (Family Deflandreoideae) from the Coniacian and Campanian (Upper Cretaceous) of the Norwegian Sea. *Review of Palaeobotany and Palynology* 271, 104080.
- Pearce, M.A., Jarvis, I., Ball, P.J., Laurin, J., 2020. Palynology of the Cenomanian to lowermost Campanian (Upper Cretaceous) Chalk of the Trunch Borehole (Norfolk, UK) and a new dinoflagellate cyst bioevent stratigraphy for NW Europe. *Review of Palaeobotany and Palynology* 278, 104188.
- Peeters, F.J.C., Hoek, R.P., Brinkhuis, H., Wilpshaar, M., Boer, P.L. De, Krijgsman, W., 1996. Differentiating glacio-eustasy and tectonics; a case study involving dinoflagellate cysts from the Eocene–Oligocene transition of the Pindos Foreland Basin (NW Greece). *Terra Nova* 10, 245–249.
- Perch-Nielsen, K., 1977. Albian to Pleistocene calcareous nannofossils from the western South Atlantic, DSDP Leg 39. Deep Sea Drilling Project, Initial Reports 39, 699–823.
- Perch-Nielsen, K., McKenzie, J., He, Q., 1982. Biostratigraphy and isotope stratigraphy and the ‘catastrophic’ extinction of calcareous nannoplankton at the Cretaceous/Tertiary boundary. *Geological Society of America, Special Papers* 190, 353–371.
- Pessagno Jr., E.A., 1977. Lower Cretaceous radiolarian biostratigraphy of the Great Valley Sequence and Franciscan Complex, California Coast Ranges. Cushman Foundation Foraminiferal Research, Special Publication 15, 5–87.
- Peybernès, B., Fondécave-Wallez, M.-J., Eichène, P., Bost, J., Sibe, B., Marais, M., Quilès, G., 1996. La limite Crétacé–Paléocène: phénomènes biologiques, événements géologiques d’après les sites de la côte basque. Centre régional de documentaion pédagogique d’Aquitaine, Bordeaux, 91 pp.
- Peyrot, D., Barroso-Barcenilla, F., Feist-Burkhardt, S., 2012. Palaeoenvironmental controls on late Cenomanian–early Turonian dinoflagellate cyst assemblages from Condemios (Central Spain). *Review of Palaeobotany and Palynology* 180, 25–40.

- Pierce, H.G., Constenius, K., 2014. Terrestrial and aquatic mollusks of the Eocene Kishenehn Formation, Middle Fork Flathead River, Montana. *Annals of Carnegie Museum* 82, 305–329.
- Pindell, J.L., 1994. Evolution of the Gulf of Mexico and the Caribbean. In: Donovan, S.K., Jackson, T.A. (Eds.), *Caribbean geology: An introduction*. University of the West Indies Press, Kingston, pp. 13–39.
- Pindell, J.L., Kennan, L., 2009. Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. *Geological Society, London, Special Publications* 328, 1–55.
- Popescue, S.-M., Dalesme, F., Jouannic, G., Escarguel, G., Head, M.J., Melinte-dobrinescu, M.C., Sütő-szentai, M., Bakrac, K., Clauzon, G., Suc, J., 2009. *Galeacysta etrusca* complex: Dinoflagellate cyst marker of paratethyan influxes to the Mediterranean sea before and after the peak of the Messinian salinity crisis. *Palynology* 33, 104–134.
- Pospelova, V., Head, M.J., 2002. *Islandinium brevispinosum* sp. nov. (Dinoflagellata), a new organic-walled dinoflagellate cyst from modern estuarine sediments of New England (USA). *Journal of Phycology* 38, 593–601.
- Pospelova, V., Chmura, G.L., Walker, H.A., 2004. Environmental factors influencing the spatial distribution of dinoflagellate cyst assemblages in shallow lagoons of southern New England (USA). *Review of Palaeobotany and Palynology* 128, 7–34.
- Pospelova, V., de Vernal, A., Pedersen, T.F., 2008. Distribution of dinoflagellate cysts in surface sediments from the northeastern Pacific Ocean (43–25°N) in relation to sea-surface temperature, salinity, productivity and coastal upwelling. *Maine Micropaleontology* 68, 21–48.
- Pospelova, V., Chmura, G.L., Boothman, W.S., Latimer, J.S., 2005. Spatial distribution of modern dinoflagellate cysts in polluted estuarine sediments from Buzzards Bay (Massachusetts, USA) embayments. *Marine Ecology Progress Series* 292, 23–40.
- Pospelova, V., Esenkulova, S., Johannessen, S.C., O'Brien, M.C., Macdonald, R.W., 2010. Organic-walled dinoflagellate cyst production, composition and flux from 1996 to 1998 in the central Strait of Georgia (BC, Canada): A sediment trap study. *Marine Micropaleontology* 75, 17–37.
- Pospelova, V., Zonneveld, K.A.F., Heikkilä, M., Bringué, M., Price, A.M., Esenkulova, S., Matsuoka, K., 2018. Seasonal, annual, and inter-annual *Spiniferites* cyst production: a review of sediment trap studies. *Palynology* 42, 162–181.
- Pospichal, J.J., Wise Jr., S.W., 1990. Calcareous nannofossils across the K/T boundary, ODP Hole 690C, Maud Rise, Weddell Sea. In: Barker, P.F., Kennett, J.P., O'Connell, S., Pisias, N.G. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results* 113, pp. 515–

532.

- Powell, A.J., 1992b. Dinoflagellate cysts of the Tertiary system. In: Powell, A.J. (Ed.), A stratigraphic index of dinoflagellate cysts. British Micropaleontological Society Publication Series, Chapman and Hall, London, pp. 155–229, pls. 4.1–4.11.
- Powell, A.J., Lewis, J., Dodge, J.D., 1992a. The palynological expressions of post-Palaeogene upwelling: a review. Geological Society, London, Special Publications 64, 215–226.
- Powell, A.J., Brinkhuis, H., Bujak, J.P., 1996. Upper Paleocene-Lower Eocene dinoflagellate cyst sequence biostratigraphy of southeast England. Geological Society, London, Special Publications 101, 145–183.
- Prasad, V., Garg, R., Khowaja-Ateequzzaman, Singh, I.B., Joachimski, M.M., 2006. *Apectodinium* acme and palynofacies characteristics in the latest Palaeocene-earliest Eocene of northeastern India: biotic response to the Palaeocene-Eocene thermal maxima (PETM) in low latitude. Journal of the Palaeontological Society of India 51, 75–91.
- Prauss, M.L., 2009. The K/Pg boundary at Brazos-River [sic], Texas, USA—An approach by marine palynology. Palaeogeography, Palaeoclimatology, Palaeoecology 283, 195–215.
- Premaor, E., Souza, P.A., Ferreira, E.P., Guerstein, G.R., Arai, M., 2018. Palinotaxonomia da seção cretácea a neogena da Bacia de Pelotas, Brasil: cistos de dinoflagelados das ordens Ptychodiscales e Gonyaulacales. Pesquisas em Geociências 45, e647.
- Premoli Silva, I., Petrizzo, M.R., Melloni, D., 2005. Data report: Planktonic foraminiferal biostratigraphy across the Cretaceous/Paleocene boundary at Shatsky Rise (ODP Leg 198, Northwest Pacific). In: Bralower, T.J., Premoli Silva, I., Malone, M.J. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results 198, College Station, Texas, pp. 1–15.
- Price, A.M., Pospelova, V., 2011. High-resolution sediment trap study of organic-walled dinoflagellate cyst production and biogenic silica flux in Saanich Inlet (BC, Canada). Marine Micropaleontology 80, 18–43.
- Price, A.M., Pospelova, V., 2014. *Spiniferites multisphaerus*, a new dinoflagellate cyst from the Late Quaternary of the Guaymas Basin, Gulf of California, Mexico. Palynology 38, 101–116.
- Price, A.M., Gurdebeke, P.R., Mertens, K.N., Pospelova, V., 2016. Determining the absolute abundance of dinoflagellate cysts in recent marine sediments III: Identifying the source of *Lycopodium* loss during palynological processing and further testing of the *Lycopodium* marker-grain method. Review of Palaeobotany and Palynology 226, 78–90.
- Price, A.M., Mertens, K.N., Pospelova, V., Pedersen, T.F., Ganeshram, R.S., 2013. Late Quaternary climatic and oceanographic changes in the northeast Pacific as recorded by dinoflagellate cysts from Guaymas Basin, Gulf of California (Mexico). Paleoceanography

28, 200–212.

- Pross, J., 2001. Paleo-oxygenation in Tertiary epeiric seas: evidence from dinoflagellate cysts. *Palaeogeography, Palaeoclimatology, Palaeoecology* 166, 369–381.
- Pross, J., Brinkhuis, H., 2005. Organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene; a synopsis of concepts. *Paläontologische Zeitschrift* 79, 53–59.
- Quattrocchio, M.E., 2009. Paleogene dinoflagellate cysts from Punta Prat, southern Chile. *Palynology* 33, 141–156.
- Rabbani, J., Ghasemi-Nejad, E., Ashoir, A., Vahidinia, M., 2015. Quantitative palynostratigraphy and palaeoecology of Tethyan Paleocene–Eocene red beds in north of Zagros sedimentary basin, Iran. *Arabian Journal of Geosciences* 8, 827–838.
- Racki, G., Machalski, M., Koeberl, C., Harasimiuk, M., 2011. The weathering-modified iridium record of a new Cretaceous–Palaeogene site at Lechówka near Chełm, SE Poland, and its palaeobiologic implications. *Acta Palaeontologica Polonica* 56, 205–215.
- Radmacher, W., Mangerud, G., Tyszka, J., 2015. Dinoflagellate cyst biostratigraphy of Upper Cretaceous strata from two wells in the Norwegian Sea. *Review of Palaeobotany and Palynology* 216, 18–32.
- Radmacher, W., Kobos, K., Tyszka, J., Jarzynka, A., Arz, J.A., 2020. Palynological indicators of palaeoenvironmental perturbations in the Basque-Cantabrian Basin during the latest Cretaceous (Zumaia, northern Spain). *Marine and Petroleum Geology* 112, 104107.
- Rankin, B.D., Stockey, R.A., Beard, G., 2008. Fruits of Icacinaceae from the Eocene Appian Way locality of Vancouver Island, British Columbia. *International Journal of Plant Sciences* 169, 305–314.
- Raub, T.D., Kirschvink, J.L., Ward, P.D., 1998. New paleomagnetic results from the Nanaimo Group, British Columbia: additional localities for testing the Baja-British Columbia Hypothesis. *Eos (Transactions, American Geophysical Union)* 79, Supplement, 223.
- Ravelo, A.C., Andreasen, D.H., Lyle, M., Lyle, A.O., Wara, M.W., 2004. Regional climate shifts caused by gradual global cooling in the Pliocene epoch. *Nature* 429, 263–267.
- Richards, B.C., 1975. *Longusorbis cuniculosus*: A new genus and species of Upper Cretaceous crab; with comments on Spray Formation at Shelter Point, Vancouver Island, British Columbia. *Canadian Journal of Earth Sciences* 12, 1850–1863.
- Riding, J.B., Head, M.J., 2018. Preparing photographic plates of palynomorphs in the digital age. *Palynology* 42, 354–365.
- Riding, J.B., Helby, R.J., 2001. Some stratigraphically significant dinoflagellate cysts from the

- Early Cretaceous (Aptian and Albian) of Australia. *Memoir of the Association of Australasian Palaeontologists* 24, 225–235.
- Riding, J.B., Mantle, D.J., Backhouse, J., 2010. A review of the chronostratigraphical ages of Middle Triassic to Late Jurassic dinoflagellate cyst biozones of the North West Shelf of Australia. *Review of Palaeobotany and Palynology* 162, 543–575.
- Rocchia, R., Boclet, D., Bonté, P., Jéhanno, C., Chen, Y., Courtillot, V., Mary, C., Wezel, F., 1990. The Cretaceous–Tertiary boundary at Gubbio revisited: vertical extent of the Ir anomaly. *Earth and Planetary Science Letters* 99, 206–219.
- Rochon, A., Lewis, J., Ellegaard, M., Harding, I.C., 2009. The *Gonyaulax spinifera* (Dinophyceae) “complex”: Perpetuating the paradox? *Review of Palaeobotany and Palynology* 155, 52–60.
- Rochon, A., Mudie, P.J., Aksu, A.E., Gillespie, H., 2002. *Pterocysta* gen. nov.: A new dinoflagellate cyst from pleistocene glacial-stage sediments of the Black and Marmara seas. *Palynology* 26, 95–105.
- Rodríguez-Tovar, F.J., Uchman, A., Molina, E., Monechi, S., 2010. Bioturbational redistribution of Danian calcareous nannofossils in the uppermost Maastrichtian across the K-Pg boundary at Bidart, SW France. *Geobios* 43, 569–579.
- Romein, A.J.T., 1977. Calcareous nannofossils from the Cretaceous/Tertiary boundary interval in the Barranco del Gredero (Caravaca, Prov. Murcia, S.E. Spain). *Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen Amsterdam, Series B* 80, 256–279.
- Rossignol, M., 1964. Hystrichosphères du Quaternaire en Méditerranée orientale, dans les sédiments Pléistocènes et les boues marines actuelles. *Revue de Micropaléontologie* 7, 83–99 (in French).
- Rouse, G.E., Hopkins Jr., W.S., Piel, K.M., 1970. Palynology of some Late Cretaceous and early Tertiary deposits in British Columbia and adjacent Alberta. *Geological Society of America, Special Papers* 127, 213–246.
- Rouse, G.E., Mathews, W.H., Blunden, R.H., 1975. The Lions Gate Member: a new Late Cretaceous sedimentary subdivision in the Vancouver area of British Columbia. *Canadian Journal of Earth Sciences* 12, 464–471.
- Rylaarsdam, J.R., Varban, B.L., Plint, A.G., Buckley, L.G., McCrea, R.T., 2006. Middle Turonian dinosaur paleoenvironments in the Upper Cretaceous Kaskapau Formation, northeast British Columbia. *Canadian Journal of Earth Sciences* 43, 631–652.
- Sager, W.W., 2005. What built Shatsky Rise, a mantle plume or ridge tectonics? *Geological Society of America, Special Papers* 388, 721–733.

- Saito, T., Yamanoi, T., Kaiho, K., 1986. End-Cretaceous devastation of terrestrial flora in the boreal Far East. *Nature* 323, 253–255.
- Salomons, W., Mook, W.G., 1981. Field observations of the isotopic composition of particulate organic carbon in the southern North Sea and adjacent estuaries. *Marine Geology* 41, M11–M20.
- Sangiorgi, F., Willard, D.A., Schouten, S., Stickley, C.E., Regan, M.O., Reichart, G., Damste, J.S.S., 2008. A 26 million year gap in the central Arctic record at the greenhouse-icehouse transition: Looking for clues. *Paleoceanography* 23, PA1S04, 1–13.
- Sarjeant, W.A.S., 1974. *Fossil and living dinoflagellates*. Academic Press, London & New York, 182 pp.
- Sarjeant, W.A.S., 1985. A restudy of some dinoflagellate cyst holotypes in the University of Kiel collections: VI. Late Cretaceous dinoflagellate cysts and other palynomorphs in the Otto Wetzel collection. *Meyniana* 37, 129–185.
- Sarjeant, W.A.S., 1986. A restudy of Pastiels' (1948) dinoflagellate cysts from the Early Eocene of Belgium. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique: Sciences de la Terre* 59, 5–43.
- Saul, L.R., Squires, R.L., 1997. New species of neritid gastropods from Cretaceous and lower Cenozoic strata of the Pacific slope of North America. *Veliger* 40, 131–147.
- Sawlowicz, Z., 1993. Iridium and other platinum-group elements as geochemical markers in sedimentary environments. *Palaeogeography, Palaeoclimatology, Palaeoecology* 104, 253–270.
- Scasso, R.A., Prámparo, M.B., Vellekoop, J., Franzosi, C., Castro, L.N., Sinninghe Damsté, J.S., 2020. A high-resolution record of environmental changes from a Cretaceous-Paleogene section of Seymour Island, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology* 555, 109844.
- Scasso, R.A., Concheyro, A., Kiessling, W., Aberhan, M., Hecht, L., Medina, F.A., Tagle, R., 2005. A tsunami deposit at the Cretaceous/Paleogene boundary in the Neuquén Basin of Argentina. *Cretaceous Research* 26, 283–297.
- Schellenberg, S.A., Brinkhuis, H., Stickley, C.E., Fuller, M., Kyte, F.T., Williams, G.L., 2004. The Cretaceous/Paleogene transition on the East Tasman Plateau, southwestern Pacific. In: Exon, N.F., Kennett, J.P., Malone, M.J. (Eds.), *The Cenozoic southern ocean: Tectonics, sedimentation and climate change between Australia and Antarctica*. American Geophysical Union, Geophysical Monograph 151, pp. 93–112.
- Schiller, J., 1930. Coccolithineae. In: Rabenhorst, L. (Ed.), *Dr. L. Rabenhorst's Kryptogamen-Flora von Deutschland, Oesterreich und der Schweiz. Zehnter Band, Flagellatae*.

Akademische Verlagsgesellschaft, Leipzig. Verlagsgesellschaft, Leipzig, pp. 89–273 (in German).

Schiøler, P., 1993. New species of dinoflagellate cysts from Maastrichtian–Danian chalks of the Danish North Sea. *Journal of Micropalaeontology* 12, 99–112.

Schiøler, P., 2005. Dinoflagellate cysts and acritarchs from the Oligocene–Lower Miocene interval of the Alma-1X well, Danish North Sea. *Journal of Micropalaeontology* 24, 1–37.

Schiøler, P., Wilson, G.J., 1993. Maastrichtian dinoflagellate zonation in the Dan Field, Danish North Sea. *Review of Palaeobotany and Palynology* 78, 321–351.

Schiøler, P., Brinkhuis, H., Roncaglia, L., Wilson, G.J., 1997. Dinoflagellate biostratigraphy and sequence stratigraphy of the Type Maastrichtian (Upper Cretaceous), ENCI Quarry, The Netherlands. *Marine Micropaleontology* 31, 65–95.

Schmitz, B., Pujalte, V., Molina, E., Monechi, S., Orue-Etxebarria, X., Speijer, R.P., Alegret, L., Apellaniz, E., Arenillas, I., Aubry, M.-P., Baceta, J.-I., Berggren, W.A., Bernaola, G., Caballero, F., Clemmensen, A., Dinarès-Turell, J., Dupuis, C., Heilmann-Clausen, C., Orús, A.H., Knox, R., Martín-Rubio, M., Ortiz, S., Payros, A., Petrizzo, M.R., Von Salis, K., Sprong, J., Steurbaut, E., Thomsen, E., 2011. The global stratotype sections and points for the bases of the Selandian (middle Paleocene) and Thanetian (upper Paleocene) stages at Zumaia, Spain. *Episodes* 34, 220–243.

Schoene, B., Samperton, K.M., Eddy, M.P., Keller, G., Adatte, T., Bowring, S.A., Khadri, S.F.R., Gertsch, B., 2015. U-Pb geochronology of the Deccan Traps and relation to the end-Cretaceous mass extinction. *Science* 347, 182–184.

Schoonen, M.A.A., 2004. Mechanisms of sedimentary pyrite formation. *Geological Society of America, Special Papers* 379, 117–134.

Schulte, P., Alegret, L., Arenillas, I., Arz, J.A., Barton, P.J., Bown, P.R., Bralower, T.J., Christeson, G.L., Claeys, P., Cockell, C.S., Collins, G.S., Deutsch, A., Goldin, T.J., Goto, K., Grajales-Nishimura, J.M., Grieve, R.Á.F., Gulick, S.P.S., Johnson, K.R., Kiessling, W., Koeberl, C., Kring, D.A., Macleod, K.G., Matsui, T., Melosh, J., Montanari, A., Morgan, J. V., Neal, C.R., Nichols, D.J., Norris, R.D., Pierazzo, E., Ravizza, G., Rebolledo-Vieyra, M., Reimold, W.U., Robin, E., Saige, T., Speijer, R.P., Sweet, A.R., Urrutia-Fucugauchi, J., Vajda, V., Whalen, M.T., Willumsen, P.S., 2010. The Chicxulub asteroid impact and mass extinction at the Cretaceous–Paleogene boundary. *Science* 327, 1214–1218.

Schumacker-Lambry, J., 1978. *Palynologie du Landenien inférieur (Paléocène) à Gelinden-Overbroek/Belgique. Relations entre les microfossiles et le sédiment. Laboratoire de Paléobotanique et de Paléopalynologie, Liège, Belgium, 157 pp., 13 pls. (in French).*

Schwartz, H., Sample, J., Weberling, K.D., Minisini, D., Moore, J.C., 2003. An ancient linked fluid migration system: cold-seep deposits and sandstone intrusions in the Panoche Hills,

- California, USA. *Geo-Marine Letters* 23, 340–350.
- Schweitzer, C.E., Feldmann, R.M., Čosović, V., Ross, R.L.M., Waugh, D.A., 2009. New Cretaceous and Eocene decapoda (Astacidea, Thalassinidea, Brachyura) from British Columbia, Canada. *Annals of Carnegie Museum* 77, 403–423.
- Schweitzer, C.E., Feldmann, R.M., Fam, J., Hessin, W.A., Hetrick, S.W., Nyborg, T.G., Ross, R.L.M., 2003. Cretaceous and Eocene decapod crustaceans from southern Vancouver Island, British Columbia, Canada. NRC Research Press, Ottawa, 66 pp.
- Schwendemann, A.B., Wang, G., Mertz, M.L., McWilliams, R.T., Thatcher, S.L., Osborn, J.M., 2007. Aerodynamics of saccate pollen and its implications for wind pollination. *American Journal of Botany* 94, 1371–1381.
- Shannon, C.E., Weaver, W., 1949. The mathematical theory of communication. University of Illinois Press, Urbana, Illinois, 117 pp.
- Shcherbinina, E., Gavrilov, Y., Iakovleva, A., Pokrovsky, B., Golovanova, O., Aleksandrova, G., 2016. Environmental dynamics during the Paleocene-Eocene thermal maximum (PETM) in the northeastern Peri-Tethys revealed by high-resolution micropalaeontological and geochemical studies of a Caucasian key section. *Palaeogeography, Palaeoclimatology, Palaeoecology* 456, 60–81.
- Shigeta, Y., Maeda, H., 2005. Yezo Group research in Sakhalin—a historical review. *National Science Museum Monographs* 31, 1–24.
- Showers, W.J., Angle, D.G., 1986. Stable isotopic characterization of organic carbon accumulation on the Amazon continental shelf. *Continental Shelf Research* 6, 227–244.
- Simpson, E.H., 1949. Measurement of diversity. *Nature* 163, 688.
- Slimani, H., 1996. Les dinokystes des craies du Campanien-Danien a Hallembaye et Turnhout (Belgique) et a Beutenaken (Pays-Bas). Supplement de systematique. *Annales de la Société Géologique de Belgique* 117, 371–391 (in French).
- Slimani, H., 2001. Les kystes de dinoflagellés du Campanien au Danien dans la région de Maastricht (Belgique, Pays-Bas) et de Turnhout (Belgique): biozonation et corrélation avec d'autres régions en Europe occidentale. *Geologica et Palaeontologica* 35, 161–201 (in French).
- Slimani, H., Toufiq, A., 2013. A Cretaceous–Palaeogene boundary geological site, revealed by planktic foraminifera and dinoflagellate cysts, at Ouled Haddou, eastern external Rif Chain, Morocco. *Journal of African Earth Sciences* 88, 38–52.
- Slimani, H., Louwye, S., Toufiq, A., 2010. Dinoflagellate cysts from the Cretaceous–Paleogene boundary at Ouled Haddou, southeastern Rif, Morocco: biostratigraphy, paleoenvironments

- and paleobiogeography. *Palynology* 34, 90–124.
- Slimani, H., Louwye, S., Toufiq, A., 2012. New species of organic-walled dinoflagellate cysts from the Maastrichtian–Danian boundary interval at Ouled Haddou, northern Morocco. *Alcheringa* 36, 337–353.
- Slimani, H., Louwye, S., Duser, M., Lagrou, D., 2011. Connecting the Chalk Group of the Campine Basin to the dinoflagellate cyst biostratigraphy of the Campanian to Danian in borehole Meer (northern Belgium). *Geologie en Mijnbouw* 90, 129–164.
- Slimani, H., Guédé, K.É., Williams, G.L., Asebriy, L., Ahmamou, M., 2016. Campanian to Eocene dinoflagellate cyst biostratigraphy from the Tahar and Sekada sections at Arba Ayacha, western External Rif, Morocco. *Review of Palaeobotany and Palynology* 228, 26–46.
- Sliter, W.V., 1968. Upper Cretaceous foraminifera from southern California and northwestern Baja California, Mexico. *University of Kansas Paleontological Contributions* 49, 141 pp.
- Sliter, W.V., 1972. Upper Cretaceous planktonic foraminiferal zoogeography and ecology—eastern Pacific margin. *Palaeogeography, Palaeoclimatology, Palaeoecology* 12, 15–31.
- Sliter, W.V., 1973. Upper Cretaceous foraminifers from the Vancouver Island area, British Columbia, Canada. *Journal of Foraminiferal Research* 3, 167–186.
- Sluijs, A., Brinkhuis, H., 2009. A dynamic climate and ecosystem state during the Paleocene–Eocene Thermal Maximum: inferences from dinoflagellate cyst assemblages at the New Jersey Shelf. *Biogeosciences* 6, 5163–5215.
- Sluijs, A., Pross, J., Brinkhuis, H., 2005. From greenhouse to icehouse; organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene. *Earth-Science Reviews* 68, 281–315.
- Sluijs, A., Brinkhuis, H., Williams, G.L., Fensome, R.A., 2009. Taxonomic revision of some Cretaceous–Cenozoic spiny organic-walled peridiniacean dinoflagellate cysts. *Review of Palaeobotany and Palynology* 154, 34–53.
- Sluijs, A., Brinkhuis, H., Stickley, C.E., Warnaar, J., Williams, G.L., Fuller, M., 2003. Dinoflagellate cysts from the Eocene–Oligocene transition in the Southern Ocean: results from ODP Leg 189. In: Exon, N.F., Kennett, J.P., Malone, M.J. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results 189*, College Station, Texas, pp. 1–42.
- Sluijs, A., Röhl, U., Schouten, S., Brumsack, H.-J., Sangiorgi, F., Sinninghe Damsté, J.S., Brinkhuis, H., 2008b. Arctic late Paleocene–early Eocene paleoenvironments with special emphasis on the Paleocene–Eocene thermal maximum (Lomonosov Ridge, Integrated Ocean Drilling Program Expedition 302). *Paleoceanography* 23, PA1S11.

- Sluijs, A., Brinkhuis, H., Crouch, E.M., John, C.M., Handley, L., Munsterman, D., Bohaty, S.M., Zachos, J.C., Reichert, G.J., Schouten, S., Pancost, R.D., Damsté, J.S.S., Welters, N.L.D., Lotter, A.F., Dickens, G.R., 2008a. Eustatic variations during the Paleocene-Eocene greenhouse world. *Paleoceanography* 23, PA4216.
- Sluyter, A., 1997. Analysis of maize (*Zea mays* subsp. *mays*) pollen: Normalizing the effects of microscope-slide mounting media on diameter determinations. *Palynology* 21, 35–39.
- Smit, J., 2005. The section of the Barranco del Gredero (Caravaca, SE Spain): a crucial section for the Cretaceous/Tertiary boundary impact extinction hypothesis. *Journal of Iberian Geology* 31, 179–191.
- Smit, J., Kyte, F.T., 1984. Siderophile-rich magnetic spheroids from the Cretaceous-Tertiary Boundary in Umbria, Italy. *Nature* 310, 403–405.
- Smit, J., Romein, A.J.T., 1985. A sequence of events across the Cretaceous-Tertiary boundary. *Earth and Planetary Science Letters* 74, 155–170.
- Smit, J., Brinkhuis, H., 1996. The Geulhemmerberg Cretaceous/Tertiary boundary section (Maastrichtian type area, SE Netherlands); summary of results and a scenario of events. *Geology en Mijnbouw* 75, 283–293.
- Smith, S.W., 1992. Microplankton from the Cape Lamb Member, López de Bertodano Formation (Upper Cretaceous), Cape Lamb, Vega Island. *Antarctic Science* 4, 337–353.
- Smith, S.Y., Currah, R.S., Stockey, R.A., 2004. Cretaceous and Eocene poroid hymenophores from Vancouver Island, British Columbia. *Mycologia* 96, 180–186.
- Smith, V., Warny, S., Vellekoop, J., Vajda, V., Escarguel, G., Jarzen, D.M., 2021. Palynology from ground zero of the Chicxulub impact, southern Gulf of Mexico. *Palynology* 45, 283–299.
- Soliman, A.L.I., 2012. Oligocene dinoflagellate cysts from the North Alpine Foreland Basin: new data from the Eggerding Formation (Austria). *Geologica Carpathica* 63, 49–70.
- Soliman, A., Slimani, H., 2019. The Cretaceous–Paleogene (K/Pg) boundary in the Dababiya Borehole, southern Egypt: An organic-walled dinoflagellate cyst approach. *Cretaceous Research* 98, 230–249.
- Soudry, D., Glenn, C.R., Nathan, Y., Segal, I., VonderHaar, D., 2006. Evolution of Tethyan phosphogenesis along the northern edges of the Arabian–African shield during the Cretaceous–Eocene as deduced from temporal variations of Ca and Nd isotopes and rates of P accumulation. *Earth-Science Reviews* 78, 27–57.
- Speijer, R.P., van der Zwaan, G.J., 1996. Extinction and survivorship of southern Tethyan benthic foraminifera across the Cretaceous/Paleogene boundary. *Geological Society,*

- London, Special Publications 102, 343–371.
- Sprain, C.J., Renne, P.R., Clemens, W.A., Wilson, G.P., 2018. Calibration of chron C29r: New high-precision geochronologic and paleomagnetic constraints from the Hell Creek region, Montana. *Geological Society of American, Bulletin* 130, 1615–1644.
- Sprain, C.J., Renne, P.R., Vanderkluyzen, L., Pande, K., Self, S., Mittal, T., 2019. The eruptive tempo of Deccan volcanism in relation to the Cretaceous-Paleogene boundary. *Science* 363, 866–870.
- Squires, R.L., 1997. Taxonomy and distribution of the buccinid gastropod *Brachysphingus* from the uppermost Cretaceous and lower Cenozoic marine strata of the Pacific slope of North America. *Journal of Paleontology* 71, 847–861.
- Squires, R.L., 2010a. Northeast Pacific Upper Cretaceous and Paleocene glycymeridid bivalves. *Journal of Paleontology* 84, 895–917.
- Squires, R.L., 2010b. Northeast Pacific record of the Cretaceous marine gastropod *Atira* and a review of its paleobiogeography. *Journal of Paleontology* 84, 1022–1030.
- Squires, R.L., Saul, L.R., 1993. A new species of *Otostoma* (Gastropoda, Neritidae) from near the Cretaceous-Tertiary boundary at Dip Creek Lake, Nacimiento, California. *Veliger* 36, 259–264.
- Squires, R.L., Saul, L.R., 2001. New Late Cretaceous gastropods from the Pacific slope of North America. *Journal of Paleontology* 75, 46–65.
- Squires, R.L., Saul, L.R., 2006. Cretaceous *Acila* (Truncacia) (Bivalvia: Nuculidae) from the Pacific slope of North America. *The Veliger* 48, 83–104.
- Srivastava, S.K., 1981. Evolution of Upper Cretaceous phytogeoprovinces and their pollen flora. *Review of Palaeobotany and Palynology* 35, 155–173.
- Srivastava, S.K., 1995. Dinocyst biostratigraphy of Santonian–Maastrichtian formations of the western Gulf Coastal Plain, southern United States. *The Palaeobotanist* 42, 249–362.
- Stanley, E.A., 1965. Upper Cretaceous and Paleocene plant microfossils and Paleocene dinoflagellates and hystrichosphaerids from northwestern South Dakota. *Bulletins of American Paleontology* 49, 179–384.
- Steeman, T., De Weirtdt, J., Smith, T., De Putter, T., Mees, F., Louwye, S., 2020. Dinoflagellate cyst biostratigraphy and palaeoecology of the early Paleogene Landana reference section, Cabinda Province, Angola. *Palynology* 44, 280–309.
- Steenbock, C.M., Stockey, R.A., Beard, G., Tomescu, A.M.F., 2011. A new family of leafy liverworts from the middle Eocene of Vancouver Island, British Columbia, Canada.

- American Journal of Botany 98, 998–1006.
- Stewart, J., Page, J., 1974. Zeolite facies metamorphism of the Late Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia. *Canadian Journal of Earth Sciences* 11, 280–284.
- Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. *Pollen et Spores* 13, 615–621.
- Stott, D.F., 1968. Lower Cretaceous Bullhead and Fort St. John groups, between Smoky and Peace rivers, Rocky Mountain Foothills, Alberta and British Columbia. Geological Survey of Canada, Bulletin 152, 1–279.
- Stott, D.F., 1982. Lower Cretaceous Fort St. John Group and Upper Cretaceous Dunvegan Formation of the foothills and plains of Alberta, British Columbia, District of Mackenzie and Yukon Territory. Geological Survey of Canada, Bulletin 328, 1–124.
- Stott, D.F., 1998. Fernie Formation and Minnes Group (Jurassic and lowermost Cretaceous), northern Rocky Mountain Foothills, Alberta and British Columbia. Geological Survey of Canada, Bulletin 516, 1–516 pp.
- Stover, L.E., Evitt, W.R., 1978. Analyses of pre-Pleistocene organic-walled dinoflagellates. Stanford University Publications, Geological Sciences 15, 1–300.
- Stover, L.E., Williams, G.L., 1987. Analyses of Mesozoic and Cenozoic organic-walled dinoflagellates 1977–1985. American Association of Stratigraphic Palynologists, Contribution Series 18, 243 pp.
- Stover, L.E., Brinkhuis, H., Damassa, S.P., de Verteuil, L., Helby, R.J., Monteil, E., Partridge, A.D., Powell, A.J., Riding, J.B., Smelror, M., Williams, G.L., 1996. Mesozoic–Tertiary dinoflagellates, acritarchs and prasinophytes. In: Jansonius, J., McGregor, D.C. (Eds.), *Palynology: principles and applications*, volume 3. Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 641–750.
- Strauss, C., Lund, J.J., Lund-Christensen, J., 2001. Miocene dinoflagellate cyst biostratigraphy of the Nieder Ochtenhausen research borehole (NW Germany). *Geologisches Jahrbuch, Reihe A* 152, 395–447.
- Streng, M., Hildebrand-Habel, T., Willems, H., 2004a. A proposed classification of archeopyle types in calcareous dinoflagellate cysts. *Journal of Paleontology* 78, 456–483.
- Streng, M., Hildebrand-Habel, T., Willems, H., 2004b. Long-term evolution of calcareous dinoflagellate associations since the Late Cretaceous: comparison of a high- and low-latitude core from the Indian Ocean. *Journal of Nannoplankton Research* 26, 13–46.
- Streng, M., Hildebrand-Habel, T., Meier, K.J.S., Fensome, R.A., 2006. Clarification of the

systematic position of two calcareous dinoflagellate taxa belonging to the genus *Calciodinellum* (Dinophyceae, Peridinales). *Micropaleontology* 52, 189–192.

- Sung Zhichen, He Chengquan, Qian Zeshu, Pan Zhaorin, Zheng Guoguang, Zheng Yuefang, 1978. On the Paleogene dinoflagellates and acritarchs from the coastal region of Bohai. Nanjing Institute of Geology and Paleontology, Academia Sinica, Nanjing, China, 190 pp., 49 pls. (in Chinese).
- Surlyk, F., Rasmussen, S.L., Boussaha, M., Schiøler, P., Schovsbo, N.H., Sheldon, E., Stemmerik, L., Thibault, N., 2013. Upper Campanian–Maastrichtian holostratigraphy of the eastern Danish Basin. *Cretaceous Research* 46, 232–256.
- Sweet, A.R., 1997. Applied research report on 2 samples from Vancouver Island, southwestern British Columbia as requested by J. Haggart. Geological Survey of Canada, Paleontological Report 06-ARS-1997, 3 pp.
- Sweet, A.R., 2005. Applied research report on four Tertiary samples from Appian Way plant locality, east coast of Vancouver Island near Campbell River (Map Area 92F/14, UTM Zone 10U 343800mE, 5531000mN). Geological Survey of Canada, Paleontological Report 02-ARS-2005, 6 pp.
- Sweet, A.R., Braman, D.R., 2001. Cretaceous–Tertiary palynofloral perturbations and extinctions within the *Aquilapollenites* Phytogeographic Province. *Canadian Journal of Earth Sciences* 38, 249–269.
- Sweet, A.R., Mustard, P.S., 2003. Palynological appraisal of Northumberland, Spray and Gabriola formations, Nanaimo Group, Hornby Island, British Columbia: a story of mixed paleogeographic and age implications. Geological Association of Canada, Mineralogical Association of Canada, Society of Economic Geologists joint annual meeting (May 25–28, Vancouver, British Columbia) abstracts volume 28, 164, 165.
- Țabără, D., Slimani, H., 2017. Dinoflagellate cysts and palynofacies across the Cretaceous–Paleogene boundary interval of the Vrancea Nappe (Eastern Carpathians, Romania). *Geological Quarterly* 61, 39–52.
- Țabără, D., Slimani, H., Mare, S., Chira, C.M., 2017. Integrated biostratigraphy and palaeoenvironmental interpretation of the Upper Cretaceous to Paleocene succession in the northern Moldavidian Domain (Eastern Carpathians, Romania). *Cretaceous Research* 77, 102–123.
- Tangen, K., Brand, L.E., Blackwelder, P.L., Guillard, R.R.L., 1982. *Thoracosphaera heimii* (Lohmann) Kamptner is a dinophyte: observations on its morphology and life cycle. *Marine Micropaleontology* 7, 193–212.
- Taylor, F.J.R., 1980. On dinoflagellate evolution. *BioSystems* 13, 65–108.

- Téllez Duarte, A.M., López Martínez, M., 2002. K-Ar dating and geological significance of clastic sediments of the Paleocene Sepultura Formation, Baja California, Mexico. *Journal of South American Earth Sciences* 15, 725–730.
- Thibault, N., Husson, D., 2016. Climatic fluctuations and sea-surface water circulation patterns at the end of the Cretaceous era: Calcareous nannofossil evidence. *Palaeogeography, Palaeoclimatology, Palaeoecology* 441, 152–164.
- Thomsen, E., Heilmann-Clausen, C., 1985. The Danian-Selandian boundary at Svejstrup with remarks on the biostratigraphy of the boundary in western Denmark. *Geological Society of Denmark, Bulletin* 33, 341–362.
- Thorn, V.C., Riding, J.B., Francis, J.E., 2009. The Late Cretaceous dinoflagellate cyst *Manumiella*—Biostratigraphy, systematics, and palaeoecological signals in Antarctica. *Review of Palaeobotany and Palynology* 156, 436–448.
- Trivett, M.L., Stockey, R.A., Rothwell, G.W., Beard, G., 2006. *Paralygodium vancouverensis* gen. et sp. nov. (Schizaeaceae): additional evidence for filicalean diversity in the Paleogene of North America. *International Journal of Plant Sciences* 167, 675–681.
- Turgeon, S.C., Creaser, R.A., 2008. Cretaceous Oceanic Anoxic Event 2 triggered by a massive magmatic episode. *Nature* 454, 323–326.
- Usher, J.L., 1952. Ammonite faunas of the Upper Cretaceous rocks of Vancouver Island, British Columbia. *Geological Survey of Canada, Bulletin* 21, 1–182.
- Vajda, V., Bercovici, A., 2014. The global vegetation pattern across the Cretaceous–Paleogene mass extinction interval: A template for other extinction events. *Global and Planetary Change* 122, 29–49.
- Vajda, V., Raine, J.I., 2003. Pollen and spores in marine Cretaceous/Tertiary boundary sediments at mid-Waipara River, North Canterbury, New Zealand. *New Zealand Journal of Geology and Geophysics* 46, 255–273.
- Vajda, V., Raine, J.I., Hollis, C.J., 2001. Indication of global deforestation at the Cretaceous–Tertiary boundary by New Zealand fern spike. *Science* 294, 1700–1702.
- Van Mourik, C.A., Brinkhuis, H., 2005. The Massignano Eocene-Oligocene golden spike section. *Stratigraphy* 2, 13–30.
- Van Mourik, C.A., Brinkhuis, H., Williams, G.L., 2001. Mid- to Late Eocene organic-walled dinoflagellate cysts from ODP Leg 171B, offshore Florida. *Geological Society, London, Special Publications* 183, 225–251.
- Vance, J.A., 1975. Bedrock geology of San Juan County. In: Russell, R.H. (Ed.), *Geology and water resources of the San Juan Islands, San Juan County, Washington*. Washington

Department of Ecology, Water Supply Bulletin 46, pp. 3–19.

- Vasilyeva, O.N., 2003. Dinocysts from deposits of the Talitsky Suites of the Trans-Urals. Yearbook 2002, Zavaritsky Institute of Geology and Geochemistry, Ural Branch, Russian academy of Sciences, 150, 20–30 (in Russian).
- Vellekoop, J., Woelders, L., Sluijs, A., Miller, K.G., Speijer, R.P., 2019. Phytoplankton community disruption caused by latest Cretaceous global warming. *Biogeosciences* 16, 1–19.
- Vellekoop, J., Smit, J., Van De Schootbrugge, B., Weijers, J.W.H., Galeotti, S., Sinninghe Damsté, J.S., Brinkhuis, H., 2015. Palynological evidence for prolonged cooling along the Tunisian continental shelf following the K–Pg boundary impact. *Palaeogeography, Palaeoclimatology, Palaeoecology* 426, 216–228.
- Vellekoop, J., Esmeray-Senlet, S., Miller, K.G., Browning, J. V, Sluijs, A., Van De Schootbrugge, B., Sinninghe Damsté, J.S., Brinkhuis, H., 2016. Evidence for Cretaceous–Paleogene boundary bolide “impact winter” conditions from New Jersey, USA. *Geology* 44, 619–622.
- Vellekoop, J., Holwerda, F., Prámparo, M.B., Willmott, V., Schouten, S., Cúneo, N.R., Scasso, R.A., Brinkhuis, H., 2017. Climate and sea-level changes across a shallow marine Cretaceous–Palaeogene boundary succession in Patagonia, Argentina. *Palaeontology* 60, 519–534.
- Verleye, T.J., Mertens, K.N., Young, M.D., Dale, B., McMinn, A., Scott, L., Zonneveld, K.A.F., Louwye, S., 2012. Average process length variation of the marine dinoflagellate cyst *Operculodinium centrocarpum* in the tropical and Southern Hemisphere oceans: Assessing its potential as a palaeosalinity proxy. *Marine Micropaleontology* 86–87, 45–58.
- Vieira, M., Mahdi, S., Osterloff, P., 2017. New early Paleocene (Danian) dinoflagellate cyst species from the Ormen Lange Field, Møre Basin, Norwegian Continental Shelf. *Palynology* 42, 180–198.
- Vink, A., 2004. Calcareous dinoflagellate cysts in South and equatorial Atlantic surface sediments: diversity, distribution, ecology and potential for palaeoenvironmental reconstruction. *Marine Micropaleontology* 50, 43–88.
- Vink, A., Zonneveld, K.A.F., Willems, H., 2000. Distributions of calcareous dinoflagellate cysts in surface sediments of the western equatorial Atlantic Ocean, and their potential use in palaeoceanography. *Marine Micropaleontology* 38, 149–180.
- Vozzhennikova, T.F., 1963. Klass Peridineae (Dinoflagellateae). Peridinei, ili dinoflagellaty. In: Kiselev, A. (Ed.), Tip Pyrrophyta. Pirrofitovye Vodorosli. In: Vakhrameeva, V.A., Radchenko, G.P., Tachmadzhana, A.L., (Eds.), Tip Pyrrophyta. Pirrofitovye Vodorosli. Vodorosli, Mochoobraznie, Psilofitovie, Plaonovidnie, Chlenistostebelnie, Paporotniki. In:

- Orlov, A., (Ed.) *Osnovy Paleontologii* 14. Moscow, Orlov, 171–186 (in Russian).
- Vozzhennikova, T.F., 1967. Iskopaemye peridinei Yurskikh, Melovykh i Paleogenovykh otlozheniy SSSR. Izdatelstvo Nauka, Moscow, U.S.S.R. 347 pp., 121 pls (Russian translation: Lees and Sarjeant, 1971).
- Wall, D., 1967. Fossil microplankton in deep-sea cores from the Caribbean Sea. *Palaeontology* 10, 95–123, pls. 14–16.
- Wall, D., Dale, B., 1970. Living hystrichosphaerid dinoflagellate spores from Bermuda and Puerto Rico. *Micropaleontology* 16, 47–58.
- Wall, D., Dale, B., 1974. Dinoflagellates in late Quaternary deep-water sediments from the Black Sea. In: Degens, E.T., Ross, D.A. (Eds.), *The Black Sea: Its Geology, Chemistry and Biology*. American Association of Petroleum Geologists, Memoir 20. pp. 364–380.
- Wall, D., Dale, B., Harada, K., 1973. Descriptions of new fossil dinoflagellates from the Late Quaternary of the Black Sea. *Micropaleontology* 19, 18–31.
- Wall, D., Dale, B., Lohmann, G.P., Smith, W.K., 1977. The environmental and climatic distribution of dinoflagellate cysts in modern marine sediments from regions in the North and South Atlantic oceans and adjacent seas. *Marine Micropaleontology* 2, 121–200.
- Waller, T.R., Marincovich Jr., L., 1992. New species of *Camptochlamys* and *Chlamys* (Mollusca: Bivalvia: Pectinidae) from near the Cretaceous/Tertiary boundary at Ocean Point, North Slope, Alaska. *Journal of Paleontology* 66, 215–227.
- Wan, X., Wignall, P.B., Zhao, W., 2003. The Cenomanian-Turonian extinction and oceanic anoxic event: Evidence from southern Tibet. *Palaeogeography, Palaeoclimatology, Palaeoecology* 199, 283–298.
- Wan, X., Jiang, T., Zhang, Y., Xi, D., Li, G., 2014. Palaeogene marine stratigraphy in China. *Lethaia* 47, 297–308.
- Wang, N., Mertens, K.N., Krock, B., Luo, Z., Derrien, A., Pospelova, V., Liang, Y., Bilien, G., Smith, K.F., De Schepper, S., Wietkamp, S., Tillmann, U., Gu, H., 2019. Cryptic speciation in *Protoceratium reticulatum* (Dinophyceae): evidence from morphological, molecular and ecophysiological data. *Harmful Algae* 88, 101610.
- Ward, P.D., 1978a. Revisions to the stratigraphy and biochronology of the Upper Cretaceous Nanaimo Group, British Columbia and Washington State. *Canadian Journal of Earth Sciences* 15, 405–423.
- Ward, P.D., 1978b. Baculitids from the Santonian-Maestrichtian Nanaimo Group, British Columbia, Canada and Washington State, USA. *Journal of Paleontology* 52, 1143–1154.

- Ward, P.D., Haggart, J.W., Mitchell, R., Kirschvink, J.L., Tobin, T., 2012. Integration of macrofossil biostratigraphy and magnetostratigraphy for the Pacific Coast Upper Cretaceous (Campanian-Maastrichtian) of North America and implications for correlation with the Western Interior and Tethys. *Geological Society of America, Bulletin* 124, 957–974.
- Warny, S.A., Wrenn, J.H., 2002. Upper Neogene dinoflagellate cyst ecostratigraphy of the Atlantic coast of Morocco. *Micropaleontology* 48, 257–272.
- Warny, S.A., Bart, P.J., Suc, J.-P., 2003. Timing and progression of climatic, tectonic and glacioeustatic influences on the Messinian Salinity Crisis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 202, 59–66.
- Wendler, J.E., Bown, P., 2013. Exceptionally well-preserved Cretaceous microfossils reveal new biomineralization styles. *Nature Communications* 4, 2052.
- Wendler, J., Willems, H., 2002. Distribution pattern of calcareous dinoflagellate cysts across the Cretaceous-Tertiary boundary (Fish Clay, Stevns Klint, Denmark): Implications for our understanding of species-selective extinction. *Geological Society of America, Special Papers* 356, 265–275.
- Westerhold, T., Röhl, U., Raffi, I., Fornaciari, E., Monechi, S., Reale, V., Bowles, J., Evans, H.F., 2008. Astronomical calibration of the Paleocene time. *Palaeogeography, Palaeoclimatology, Palaeoecology* 257, 377–403.
- Wetzel, O., 1933. Die in organischer Substanz Erhaltenen Mikrofossilien des baltischen Kreide-Feuersteins mit einem sediment-petrographischen und stratigraphischen Anhang. *Palaeontographica, Abteilung A* 78, 1–110, pls. 1–4 (in German).
- Wetzel, O., 1940. Mikropaläontologische Untersuchungen an der obersten Kreide von Stevns Klint-Kridtbrud auf der dänischen Insel Seeland und an ihrem Feuerstein in geschiebekundlicher Hinsicht. *Zeitschrift für Geschiebeforschung* 16, 118–165 (in German).
- Wetzel, O., 1952. Beitrag zur Kenntnis des dan-zeitlichen Meeresplanktons. *Geologisches Jahrbuch* 66, 391–419 (in German).
- Wetzel, O., 1961. New microfossils from Baltic Cretaceous flintstones. *Micropaleontology* 7, 337–350.
- Wiggin, N.J., Riding, J.B., Franz, M., 2017. Resolving the Middle Jurassic dinoflagellate radiation: The palynology of the Bajocian of Swabia, southwest Germany. *Review of Palaeobotany and Palynology* 238, 55–87.
- Williams, G.L., Downie, C., 1966. Further dinoflagellate cysts from the London Clay. In: Davey, R.J., Downie, C., Sarjeant, W.A.S., Williams, G.L. (Eds.), *Studies on Mesozoic and Cainozoic dinoflagellate cysts. Bulletin of the British Museum (Natural History), Geology*

Supplement 3, pp. 215–236, pls. 24–26.

- Williams, G.L., Brideaux, W.W., 1975. Palynologic analyses of upper Mesozoic and Cenozoic rocks of the Grand Banks, Atlantic Continental Margin. Geological Survey of Canada, Bulletin 236, 1–68, pls. 1–47.
- Williams, G.L., Lentin, J.K., Fensome, R., 1998. The Lentin and Williams index of fossil dinoflagellates 1998 edition. American Association of Stratigraphic Palynologists, Contribution Series 34, 817 pp.
- Williams, G.L., Fensome, R.A., MacRae, R.A., 2017. DINOFLAJ3. American Association of Stratigraphic Palynologists, Data Series 2.
- Williams, G.L., Damassa, S.P., Fensome, R.A., Guerstein, G.R., 2015. *Wetzeliiella* and its allies—the “hole” story: A taxonomic revision of the Paleogene dinoflagellate subfamily Wetzeliielloideae. Palynology 39, 289–344.
- Williams, G.L., Brinkhuis, H., Pearce, M.A., Fensome, R.A., Weegink, J.W., 2004. Southern Ocean and global dinoflagellate cyst events compared: index events for the Late Cretaceous–Neogene. In: Exon, N.F., Kennett, J.P., Malone, J.M. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results 189, College Station, Texas, pp. 1–98.
- Willumsen, P.S., 2011. Maastrichtian to Paleocene dinocysts from the Clarence Valley, South Island, New Zealand. Alcheringa 35, 199–240.
- Willumsen, P.S., 2012. Three new species of dinoflagellate cyst from Cretaceous–Paleogene (K–Pg) boundary sections at mid- Waipara River and Fairfield Quarry, South Island, New Zealand. Palynology 36, 48–62.
- Wilson, G.J., 1974. Upper Campanian and Maastrichtian dinoflagellate cysts from the Maastricht region and Denmark (unpubl. PhD thesis). University of Nottingham, Nottingham, United Kingdom, 601 pp.
- Wilson, G.J., 1984. New Zealand Late Jurassic to Eocene dinoflagellate biostratigraphy—a summary. Newsletters on Stratigraphy 13, 104–117.
- Wilson, G.J., 1988. Paleocene and Eocene dinoflagellate cysts from Waipawa, Hawkes Bay, New Zealand. New Zealand Geological Survey, Paleontological Bulletin 57, 1–96.
- Wilson, G.. J., Clowes, C.D., 1980. A concise catalogue of organic-walled fossil dinoflagellate genera. New Zealand Geological Survey Report 92, 1–199.
- Witts, J.D., Whittle, R.J., Wignall, P.B., Crame, J.A., Francis, J.E., Newton, R.J., Bowman, V.C., 2016. Macrofossil evidence for a rapid and severe Cretaceous–Paleogene mass extinction in Antarctica. Nature Communications 7, 1–9.

- Woelders, L., Speijer, R.P., 2015. Stable seafloor conditions, sea level and food supply during the latest Maastrichtian at Brazos River, Texas. *Marine Micropaleontology* 121, 41–51.
- Woelders, L., Vellekoop, J., Weltje, G.J., De Nooijer, L., Reichart, G.-J., Peterse, F., Claeys, P., Speijer, R.P., 2018. Robust multi-proxy data integration, using Late Cretaceous paleotemperature records as a case study. *Earth and Planetary Science Letters* 500, 215–224.
- Woelders, L., Vellekoop, J., Kroon, D., Smit, J., Casadío, S., Prámparo, M.B., Dinarès-Turell, J., Peterse, F., Sluijs, A., Lenaerts, J.T.M., Speijer, R.P., 2017. Latest Cretaceous climatic and environmental change in the South Atlantic region. *Paleoceanography* 32, 466–483.
- Wood, E.J.F., 1955. Fluorescent microscopy in marine microbiology. *Journal du Conseil, Conseil Permanent International pour l'Exploration de la Mer* 21, 6–7.
- Worden, R.H., Morrall, G.T., Kelly, S., McArdle, P., Barshep, D.V., 2019. A renewed look at calcite cement in marine-deltaic sandstones: the Brent Reservoir, Heather Field, northern North Sea, UK. *Geological Society, London, Special Publications* 484, SP484-2018-43.
- Wrenn, J.H., 1988. Differentiating species of the dinoflagellate cyst genus *Nematosphaeropsis* Deflandre & Cookson 1955. *Palynology* 12, 129–150.
- Wrenn, J.H., Hart, G.F., 1988. Paleogene dinoflagellate cyst biostratigraphy of Seymour Island, Antarctica. *Geological Society of America, Memoir* 169, 321–447.
- Wright, A.A., 1985. Introduction, cruise summary, and explanatory notes: Deep Sea Drilling Project Leg 86, western North Pacific. *Deep Sea Drilling Project, Initial Reports* 86, 5–21.
- Wright, A.A., Bleil, U., Monechi, S., Michel, H.V, Shackleton, N.J., Simoneit, B.R.T., Zachos, J.C., 1985. Summary of Cretaceous/Tertiary boundary studies, Deep Sea Drilling Project Site 577, Shatsky Rise. *Deep Sea Drilling Project, Initial Reports* 86, 799–804.
- Yu, J., 1989. Dinoflagellates. In: *Research Party of Marine Geology, Ministry of Geology and Mineral Resources and Institute of Geology, Chinese Academy of Geological Sciences (Eds.), Cenozoic Paleobiota of the Continental Shelf of the East China Sea (Donghai), Micropaleobotanical Volume*. Geological Publishing Press, Beijing, pp. 112–159 (in Chinese).
- Zachos, J.C., Arthur, M.A., 1986. Paleoclimatology of the Cretaceous-Tertiary boundary event: inferences from stable isotopic and other data. *Paleoclimatology* 1, 5–26.
- Zachos, J.C., Arthur, M.A., Deant, W.E., 1989. Geochemical evidence for suppression of pelagic marine productivity at the Cretaceous/Tertiary boundary. *Nature* 337, 61–64.
- Zachos, J.C., Arthur, M.A., Thunell, R.C., Williams, D.F., Tappa, E.J., 1985. Stable isotope and trace element geochemistry of carbonate sediments across the Cretaceous/Tertiary boundary

at Deep Sea Drilling Project Hole 577, Leg 86. Deep Sea Drilling Project, Initial Reports 86, 513–532.

- Zakharov, Y.D., Ignatyev, A.V., Ukhaneva, N.G., Afanaseva, T.B., 1996. Cretaceous ammonoid succession in the Far East (south Sakhalin) and the basic factors of syngeneses. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique: Sciences de la Terre* 66, 109–127.
- Zakharov, Y.D., Haggart, J.W., Beard, G., Safronov, P.P., 2013. Late Cretaceous climatic trends and a positive carbon isotope excursion at the Santonian-Campanian boundary in British Columbia, northeastern Pacific. *Sedimentary Geology* 295, 77–92.
- Zonneveld, K.A.F., Brune, A., Willems, H., 2000. Spatial distribution of calcareous dinoflagellate cysts in surface sediments of the Atlantic Ocean between 13°N and 36°S. *Review of Palaeobotany and Palynology* 111, 197–223.
- Zonneveld, K.A.F., Versteegh, G.J.M., de Lange, G.J., 2001. Palaeoproductivity and post-depositional aerobic organic matter decay reflected by dinoflagellate cyst assemblages of the eastern Mediterranean S1 sapropel. *Marine Geology* 172, 181–195.
- Zonneveld, C.A.F., Bockelmann, F., Holzwarth, U., 2007. Selective preservation of organic walled dinoflagellate cysts as a tool to quantify past net primary production and bottom water oxygen concentrations. *Marine Geology* 237, 109–126.
- Zonneveld, K.A.F., Versteegh, G., Kodrans-nsiah, M., 2008. Preservation and organic chemistry of Late Cenozoic organic-walled dinoflagellate cysts: A review. *Marine Micropaleontology* 68, 179–197.
- Zonneveld, K.A.F., Sebastian Meier, K.J., Esper, O., Siggelkow, D., Wendler, I., Willems, H., 2005. The (palaeo-) environmental significance of modern calcareous dinoflagellate cysts: a review. *Paläontologische Zeitschrift* 79, 61–77.
- Zonneveld, K.A.F., Marret, F., Versteegh, G.J.M., Bogus, K., Bonnet, S., Bouimetarhan, I., Crouch, E., de Vernal, A., Elshanawany, R., Edwards, L., Esper, O., Forke, S., Grøsfjeld, K., Henry, M., Holzwarth, U., Kielt, J.-F., Kim, S.-Y., Ladouceur, S., Ledu, D., Chen, L., Limoges, A., Londeix, L., Lu, S.-H., Mahmoud, M.S., Marino, G., Matsouka, K., Matthiessen, J., Mildenhall, D.C., Mudie, P., Neil, H.L., Pospelova, V., Qi, Y., Radi, T., Richerol, T., Rochon, A., Sangiorgi, F., Solignac, S., Turon, J.-L., Verleye, T., Wang, Y., Wang, Z., Young, M., 2013. Atlas of modern dinoflagellate cyst distribution based on 2405 data points. *Review of Palaeobotany and Palynology* 191, 1–197.

Appendices

Appendix 1.A. List of palynological taxa observed in the Oyster Bay Formation and supplementary figures

Information in brackets after each entry corresponds to the following format: **figure**, sample number, slide ID, England Finder coordinates. We acknowledge that coordinates may be offset between the stages of different microscopes of this model. Nevertheless, coordinates have been included to provide starting points of reference. Supplementary figures are provided for representative specimens of taxa herein placed in open nomenclature not included in the main study (denoted as “SFig.”).

Dinoflagellate cysts

- Achomosphaera* cf. *minor* He Chengquan, 1991 (**SFig. 1S**, 64, 19-68A, B33/4)
- Achomosphaera* cf. *sagena* Davey and Williams, 1966a (**Fig. 5G**, 26, 18-212A, P35/3)
- Achomosphaera* sp. (**SFig. 1M**, 29, 18-213C, W25/2)
- Alisocysta margarita* Harland, 1979 (**Fig. 5C**, 90, 17-694A, J31/3)
- Andalusiella gabonensis* (Stover and Evitt, 1978) Wrenn and Hart, 1988 (**Fig. 7T**, 77, 17-691D, X39/0)
- Apteodinium* cf. *cornutum* Cookson and Eisenack, 1974 (**SFig. 2K**, 23, 18-211A, Y34/4)
- Apteodinium* cf. *fallax* (Morgenroth, 1968) Stover and Evitt, 1978 (**SFig. 2J**, 77, 17-691C, F29/0)
- Areoligera* ‘*circumcoronata*’ of Fensome and Williams (2005) (name not effectively published)
- Areoligera circumsenonensis* Fensome et al., 2009
- Areoligera volata* Drugg, 1967 (**Fig. 5X**, 62, 18-178A, O50/1)
- Batiacasphaera* cf. *solida* Slimani, 2003 (**SFig. 2L**, 67, 19-71A, J39/3)
- Canningia glomerata* (Clarke and Verdier, 1967) Fensome et al., 2019
- Canningia reticulata* (Cookson and Eisenack, 1960b) Helby, 1987
- Cannosphaeropsis franciscana* Damassa, 1979b (**Fig. 5M**, 21, 18-184F, T40/2)
- Cerodinium diebelii* (Alberti, 1959) Lentin and Williams, 1987 (**Fig. 7S**, 21, 18-184B, H37/1)
- Cerodinium* cf. *kangiliense* Hansen in Nøhr-Hansen and Heilmann-Clausen, 2001 (**SFig. 1I, J**, 60, 18-179B, G28/4)
- Cordosphaeridium fibrospinosum* (Davey and Williams, 1966b) Davey, 1969 (**Fig. 6P**, 21, 18-184E, S43/2)
- Cordosphaeridium inodes* (Klumpp, 1953) Sarjeant, 1981 (**Fig. 6Q**, 49, 18-229A, M43/4)
- Cordosphaeridium* sp. A (**SFig. 2F**, 75, 17-689C, M30/0)

- Cordosphaeridium* sp. B (**SFig. 2I**, 53, 19-63A, H27/0)
- Cyclonephelium compactum* (Deflandre and Cookson, 1955) Fensome et al., 2019 (**Fig. 5V**, 54, 18-182B, T43/0)
- Danea californica* (Drugg, 1967) Stover and Evitt, 1978 (**Fig. 6R**, 62, 18-178B, O33/0)
- Danea* cf. *heterospinosa* Matsuoka, 1983 (**SFig. 2A**, 62, 18-178B, L45/4; **SFig. 2B**, 62, 18-178B, N43/1)
- Danea impages* Damassa, 1979a
- Danea* cf. *impages* Damassa, 1979a (**SFig. 2C, D**, 33, 18-215A, C39/4)
- Danea?* sp. (**SFig. 2E**, 53, 19-63A, J22/4)
- Deflandrea galeata* (Lejeune-Carpentier, 1942) Lejeune-Carpentier and Sarjeant, 1981 (**Fig. 7R**, 67, 19-71B, M29/0)
- Deflandrea oebisfeldensis* Alberti, 1959 (**Fig. 7Q**, 85, 17-693A, Z36/1)
- Diconodinium* cf. *sinense* He Chengquan, 1991 (**SFig. 1K, L**, 31, 18-214B, J42/0)
- Dinogymnium cretaceum* (Deflandre, 1936) Evitt et al., 1967 (**Fig. 5L**, 26, 18-212B, M28/2)
- Dinogymnium digitus* (Deflandre, 1936) Evitt et al., 1967 (**Fig. 5Q**, 22, 19-36A, W36/4)
- Diphyes colligerum* (Deflandre and Cookson, 1955) Goodman and Witmer, 1985 (**Fig. 6D**, 75, 17-689E, O35/3)
- Diphyes digitum* Awad and Oboh-Ikuenobe, 2016 (**Fig. 6E**, 80, 19-79A, W37/4)
- Eisenackia reticulata* (Damassa, 1979b) Quattrocchio and Sarjeant, 2003 (**Fig. 5D**, 90, 17-694A, H45/3)
- Eocladopyxis?* sp. (**SFig. 2G**, 60, 18-179A, L42/0; **SFig. 2H**, 60, 18-179A, K40/3)
- Exochosphaeridium bifidum* (Clarke and Verdier, 1967) Clarke et al., 1968 (**Fig. 6G**, 62, 18-178B, Z39/4)
- Exochosphaeridium majus* (Lejeune-Carpentier, 1940) Peyrot, 2011
- Exochosphaeridium phragmites* Davey et al., 1966 (**Fig. 6H**, 69, 19-72B, V35/0; **Fig. 6I**, 81, 19-80A, Q38/4)
- Fibradinium annetorpense* Morgenroth, 1968 (**Fig. 5B**, 62, 18-178A, H42/2)
- Florentinia ferox* (Deflandre, 1937) Duxbury, 1980 (**Fig. 6F**, 90, 18-694C, W32/1)
- Ginginodinium* cf. sp. A of Steeman et al. (2020) (**Fig. 7M**, 85, 17-693G, M22/1; **Fig. 7N**, **SFig. 1A**, 90, 17-694D, M46/0)
- Glaphyrocysta divaricata* (Williams and Downie, 1966) Stover and Evitt, 1978 (**Fig. 5W**, 35, 18-216A, T27/0)
- Glaphyrocysta perforata* Hultberg and Malmgren, 1985
- Glyphanodinium facetum* Drugg, 1964 (**Fig. 5A**, 90, 17-694A, G29/2)
- Hafniasphaera delicata* Fensome et al., 2009
- Hafniasphaera fluens* Hansen, 1977
- Hafniasphaera septata* (Cookson and Eisenack, 1967) Hansen, 1977 (**Fig. 5J**, 21, 18-184A, Q45/3)

- Hafniasphaera* sp. (**SFig. 1N**, 78, 17-692D, F36/3)
- Hystriocholpoma torquatum* Damassa, 1979a
- Hystriosphæridium tubiferum* (Ehrenberg, 1837) Davey and Williams, 1966b (**Fig. 5R**, 21, 18-184B, O48/1)
- Ifecysta fusiforma* Antolinez-Delgado and Oboh-Ikuenobe, 2007 (**Fig. 6N**, 60, 18-179B, J31/1)
- Ifecysta lappacea* (Drugg, 1970) Antolinez-Delgado and Oboh-Ikuenobe, 2007 (**Fig. 6M**, 50, 19-61A, R33/3)
- Ifecysta pachyderma* Jan du Chêne and Adediran, 1984 (**Fig. 6O**, 62, 18-178A, L36/0)
- Impagidinium gracilium* Shaw, 1999
- Impagidinium?* sp. (**SFig. 2P, Q**, 32, 19-99B, P23/0)
- Impagidinium* spp. (**SFig. 2O**, 88, 18-176B, H49/0)
- Kenleyia lophophora* Cookson and Eisenack, 1965a (**Fig. 6K**, 45, 18-225C, D28/0)
- Kenleyia pachycerata* Cookson and Eisenack, 1965a (**Fig. 6J**, 41, 18-222A, G35/0)
- Kiokansium* sp. of Nøhr-Hansen (1994) (**Fig. 5F**, 21, 18-184A, L33/0)
- Laciniadinium arcticum* (Manum and Cookson, 1964) Lentin and Williams, 1980 (**Fig. 7B**, 62, 18-178B, Q53/3)
- Lanternosphaeridium lanosum* Morgenroth, 1966 (**Fig. 6S**, 32, 19-99A, H38/1)
- Lejeunecysta globosa* Biffi and Grignani, 1983
- Lejeunecysta* cf. *hyalina* (Gerlach, 1961) Artzner and Dörhöfer, 1978 (**Fig. 7O**, 74, 17-690D, Y34/2)
- Lejeunecysta lata* Biffi and Grignani, 1983 (**Fig. 7P**, 74, 17-690C, Q44/0)
- Leptodinium* sp. (**SFig. 1P, Q**, 87, 18-235B, B33/3)
- Maduradinium pentagonum* Cookson and Eisenack, 1970a (**Fig. 6J**, 74, 17-690C, E33/1)
- Maduradinium* sp. (**Fig. 7I**, 75, 17-689D, K44/4)
- Muratodinium fimbriatum* (Cookson and Eisenack, 1967) Drugg, 1970 (**Fig. 6L**, 20, 19-35A, C32/0)
- Nematosphaeropsis* cf. *philippotii* (Deflandre, 1947a) de Coninck, 1968 (**SFig. 1V**, 90, 17-694A, G44/0)
- Octodinium askiniae* Wrenn and Hart, 1988
- Operculodinium* cf. *eirikianum* Head et al., 1989 (**Fig. 6C**, 76, 19-77A, V43/4)
- Operculodinium minutum* He Chengquan, 1991 (**Fig. 6A**, 90, 17-694A, G41/3)
- Operculodinium taiwanianum* Shaw, 1999 (**Fig. 6B**, 49, 18-229A, L31/2)
- Palaeocystodinium golzowense* Alberti, 1961 (**Fig. 7U**, 21, 18-184A, G/45/4)
- Palaeocystodinium* cf. *lidiae* Górka, 1963 (**SFig. 1F**, 21, 18-184F, R29/3)
- Palaeocystodinium* cf. *minor* (**SFig. 1G**, 26, 18-212B, Q28/4)
- Palaeoperidinium pyrophorum* (Ehrenberg ex Wetzell, 1933) Evitt et al., 1998 (**Fig. 7H**, 88, 18-176B, C40/4)

- Palynodinium grallator* Gocht, 1970 (**Fig. 5S**, 21, 18-184B, J39/1; **Fig. 5T**, 21, 18-184F, W40/0)
- Phelodinium* spp. (**SFig. 1D**, 74, 17-690C, K33/2; **SFig. 1E**, 74, 17-690D, K45/1)
- Pterodinium* cf. *ayachense* Guédé et al., 2014 (**SFig. 1O**, 90, 17-694D, X25/1)
- Senegalinium dilwynense* (Cookson and Eisenack, 1965b) Stover and Evitt, 1978 (**Fig. 7C**, **SFig. 1B**, 74, 17-690D, J28/0; **Fig. 7D**, 75, 17-689C, Y44/2)
- Senegalinium microgranulatum* (Stanley, 1965) Stover and Evitt, 1978 (**Fig. 7F**, 21, 18-184F, Z31/2)
- Senegalinium obscurum* (Drugg, 1967) Stover and Evitt, 1978 (**Fig. 7E**, 90, 17-694C, O35/3)
- Senegalinium* sp. (**SFig. 1H**, 75, 17-689D, S47/1)
- Senoniasphaera inornata* (Drugg, 1970) Stover and Evitt, 1978 (**Fig. 5U**, 21, 18-184C, K49/0)
- Sentusidinium granulosa* (**SFig. 2X**, 77, 17-691C, L32/1)
- Spinidinium bellum* Lucas-Clark, 2006 (**Fig. 7K**, **SFig. 1C**, 74, 17-690C, G35/0)
- Spinidinium densispinatum* Stanley, 1965 (**Fig. 7L**, 26, 18-212A, V45/3)
- Spinidinium echinoidum* (Cookson and Eisenack, 1960a) Lentin and Williams, 1976
- Spiniferella cornuta* subsp. *cornuta* (Gerlach, 1961) Stover and Hardenbol, 1994
- Spiniferella cornuta* cf. subsp. *cornuta* (Gerlach, 1961) Stover and Hardenbol, 1994 (**Fig. 5N**, 74, 17-690D, U39/1)
- Spiniferites–Nematosphaeropsis* sp. (**SFig. 1W**, 29, 18-213A, L48/1)
- Spiniferites* cf. *hyperacanthus* (Deflandre and Cookson, 1955) Cookson and Eisenack, 1974 of Jan du Chêne (1988) (**Fig. 5H**, 62, 18-178B, R45/4)
- Spiniferites* cf. *mirabilis* (Rossignol, 1964) Sarjeant, 1970 of Jan du Chêne (1988) (**Fig. 5I**, 75, 17-689C, U49/3)
- Spiniferites pseudofurcatus* (Klumpp, 1953) Sarjeant, 1981 (**Fig. 5O**, 51, 18-230B, R45/2)
- Spiniferites ramosus* (Ehrenberg, 1837) Mantell, 1854 subsp. *granosus* (Davey and Williams, 1966a) Lentin and Williams, 1973
- Spiniferites* cf. sp. of Oboh-Ikuenobe et al. (2017) (**SFig. 1U**, 33, 18-215B, V36/4)
- Spiniferites* sp. A (**SFig. 1T**, 33, 18-215A, E35/0)
- Spiniferites* sp. B (**SFig. 1R**, 26, 18-212A, V42/0)
- Spiniferites* complex (**Fig. 5P**, 53, 19-63C, D33/1)
- Stephodinium?* sp. (**SFig. 2M**, **N**, 90, 17-694A, F37/1)
- Tanyosphaeridium xanthiopyxides* (Wetzel ex Deflandre, 1937) Sarjeant, 1985 (**Fig. 5K**, 90, 17-694A, T45/0)
- Tanyosphaeridium* sp. (**SFig. 2V**, **W**, 88, 18-176A, G30/1)
- Tenua hystrix* (Eisenack, 1958) Fensome et al. 2019
- Turbiosphaera galatea* Eaton, 1976

Turbiosphaera magnifica Eaton, 1976 (**Fig. 6A**, 35, 18-216B, M45/3)

Vozzhennikovia cf. *minus* (He Chengquan and Wang Kede, 1990) Sluijs et al., 2009 (**Fig. 7A**, 59, 18-180B, M47/1)

Xenicodinium delicatum Hultberg, 1985 (**Fig. 5E**, 77, 17-691C, N41/0)

Xenikoon australis Cookson and Eisenack, 1960a (**Fig. 7G**, 81, 19-80A, F38/0)

Cyst Type A (**SFig. 2R**, S, 90, 17-694A, L34/4)

Cyst Type B (**SFig. 2T**, 31, 18-214B, X33/4)

Cyst Type C (**SFig. 2U**, 53, 19-63A, H39/0)

Other marine palynological constituents

Baltisphaeridium cf. *crameri* Singh, 1971 (**Fig. 8H**, 85, 17-693A, F29/3)

Cymatiosphaera sp. (**SFig. 3A**, B, 88, 18-176B, K41/4)

Corbisema hastata globulata Bukry, 1976 (**Fig. 8A**, 77, 17-691D, C35/3)

Fromea sp. (**SFig. 3H**, 90, 17-694A, R30/4)

Medlinia weissei (Grunow ex Witt, 1885) Sims, 1998 (**Fig. 8B**, 77, 17-691C, G40/1)

Michrhystridium fragile Deflandre, 1947b (**Fig. 8F**, 75, 17-689C, D38/0)

Paralecaniella indentata (Deflandre and Cookson, 1955) Cookson and Eisenack, 1970b (**Fig. 8G**, 90, 17-694C, E48/3)

Pterospermopsis aureolata Cookson and Eisenack, 1958 (**Fig. 8J**, 90, 17-694A, E44/2)

Pterospermopsis danica (Wetzel, 1952) Sarjeant, 1984 (**Fig. 8I**, 86, 19-83B, N26/4)

Chorate acritarchs (**SFig. 3C**, 90, 17-694A, F39/0)

Foraminiferal organic linings (**Fig. 8K**, 90, 17-694C, T45/1; **Fig. 8L**, 85, 17-693A, K38/4)

Scolecodonts (**Fig. 8C**, 77, 17-691C, C35/4; **Fig. 8D**, 74, 17-690D, F44/4; **Fig. 8E**, 27, 19-39A, G31/0)

Terrestrial palynomorphs

Alisporites spp. (**SFig. 3S**, 90, 17-694D, B39/4)

Chenopodipollis? sp. (**SFig. 3N**, 23, 18-211A, Q49/4)

Concavissimisporites sp. (**Fig. 8Y**, 88, 18-176A, X39/0)

Deltoidospora sp. (**Fig. 8BB**, 41, 18-222A, V26/4)

Echinatisporis sp. A (**Fig. 8U**, 34, 19-100A, G45/0)

Ephedripites sp. (**Fig. 8M**, 37, 18-218A, W27/3)

Gleicheniidites spp. (**SFig. 3K**, 59, 18-180A, V40/4)

Laevigatosporites spp. (**SFig. 3I**, 45, 18-225C, Y34/0)

Lycopodiacidites sp. (**Fig. 8Z**, 30, 19-98B, T27/0)

Margocolporites sp. (**Fig. 8X**, 90, 17-694A, L40/4)

Momipites sp. (**Fig. 8P**, 22, 19-36A, Q31/3)

Ornamentifera baculata Singh, 1971

Osmundacidites sp. (**Fig. 8W**, 26, 18-212A, M48/3)

Parviprojectus reductus (Norton, 1965) Braman, 2013 (**Fig. 8N**, 25, 19-38A, P28/2)

Parviprojectus sp. (**SFig. 3P**, 30, 19-98A, J29/1)

Piceapollenites spp. (**SFig. 3T**, 55, 19-64C, O31/1)

Podocarpidites sp. A (**Fig. 8O**, 60, 18-179B, S35/4)

Podocarpidites sp. B (**SFig. 3R**, 74, 17-690C, M30/0)

Propylipollis sp. (**Fig. 8T**, 85, 17-693G)

Stereisporites sp. (**SFig. 3J**, 88, 18-176B, J40/3)

Tricolpites sp. cf. pollen of *Gynoplatananthus oysterbayensis* Mindell et al., 2006 (**Fig. 8Q**, 90, 17-694A, K45/1)

Tricolpites spp. (**SFig. 3O**, 85, 17-693A, N49/1)

Tricolporites sp. (**SFig. 3Q**, 25, 19-38B, P45/3)

Trilobosporites sp. (**Fig. 8AA**, 78, 17-692E, S44/0)

Trilobosporites spp. (**SFig. 3L**, 33, 18-215A, L25/4)

Triporopollenites sp. (**SFig. 3M**, 86, 19-83A, D41/0)

Tschudypollis thalmannii (Anderson, 1960) Nichols, 2002 (**Fig. 8R**, 88, 18-176A, F42/0)

Tschudypollis sp. (**Fig. 8S**, 74, 17-690D, G44/4)

Trilites sp. (**Fig. 8V**, 39, 18-220A, F36/1)

Palynomorphs *incertae sedis*

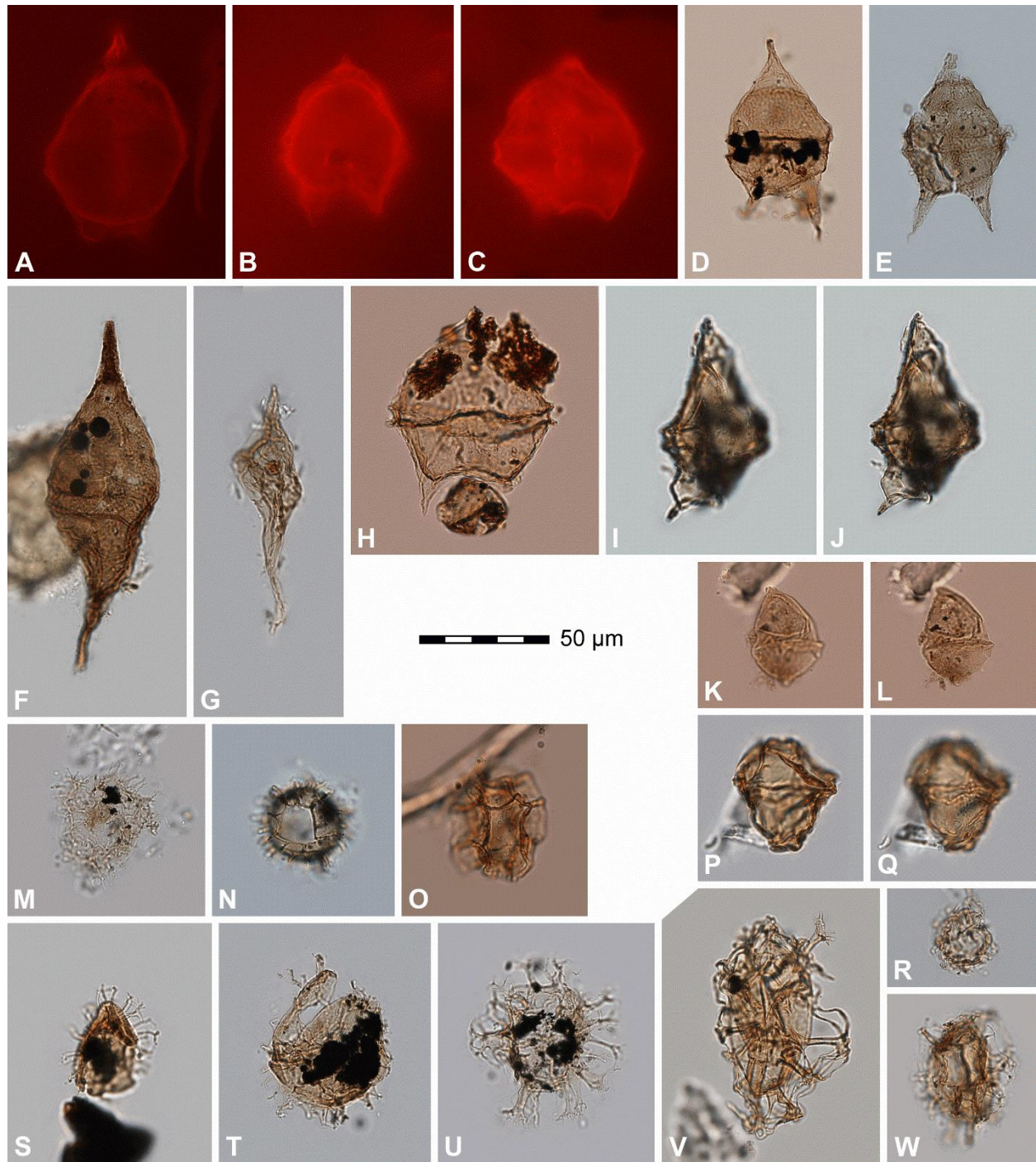
Coronate Palynomorph Type A (**SFig. 3D**, 90, 17-694A, M45/2)

Coronate Palynomorph Type B (**SFig. 3E**, 77, 17-691C, D31/2)

Kalyptrate Palynomorph Type A (**SFig. 3G**, 90, 17-694C, V38/1)

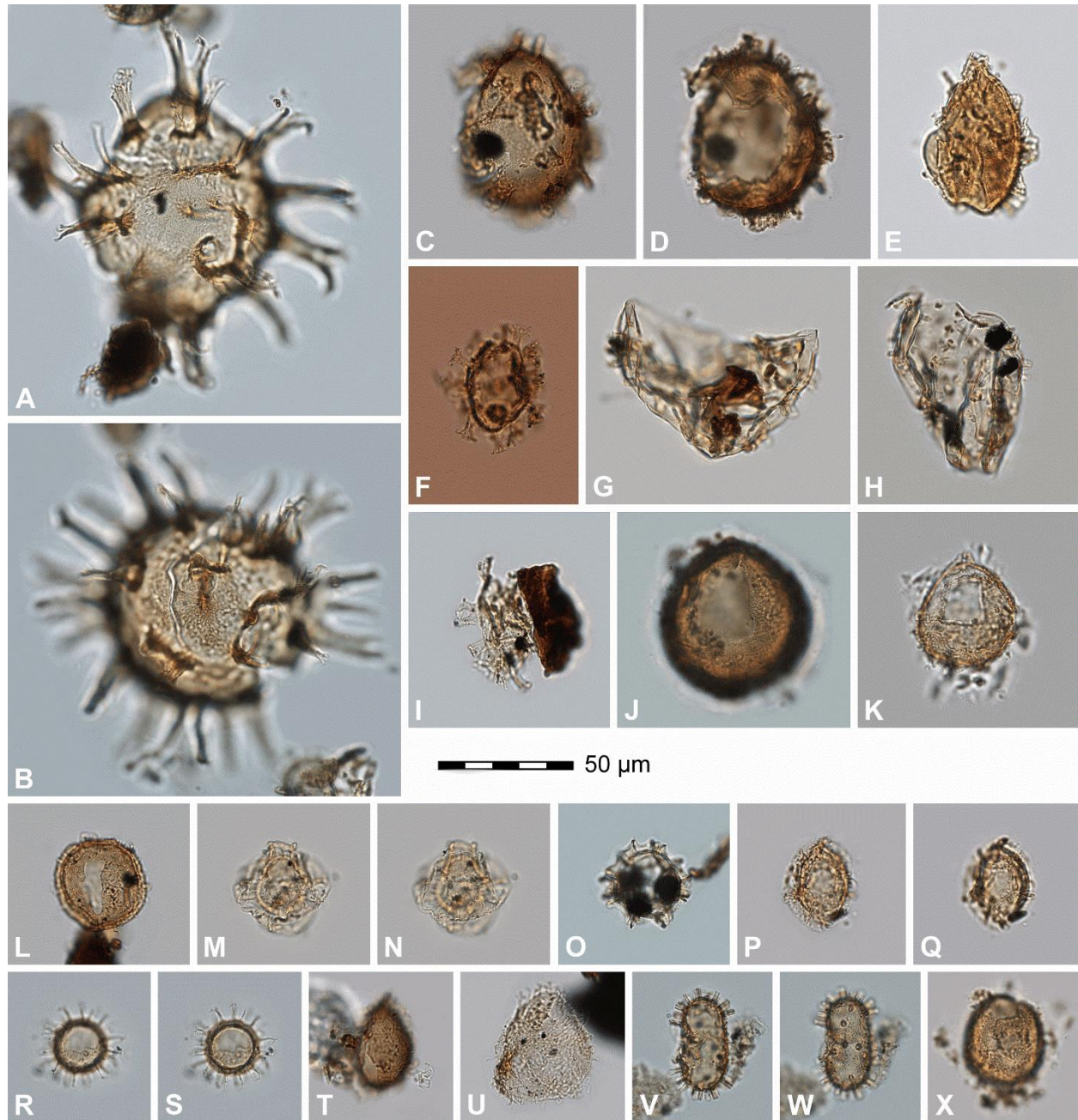
Kalyptrate Palynomorph Type B (**SFig. 3F**, 21, 18-184B, E42/2)

Nondescript Translucent Palynomorphs



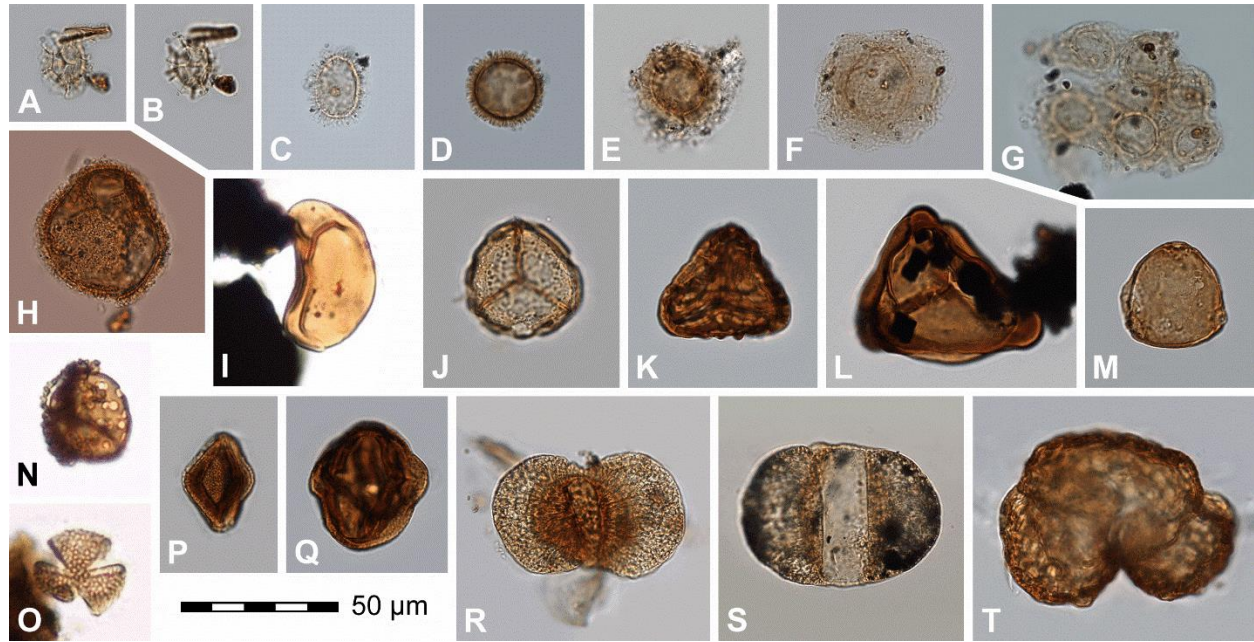
Supplementary Fig. 1. Epifluorescence and bright-field photomicrographs of selected dinoflagellate cysts. Specimen samples and positions in brackets. Section abbreviations: AW, Appian Way; LN, Lynnwood; OR, Oyster River. **A**, *Gingiodinium* cf. sp. A of Steeman et al. (2020) (85, AW ~30–31.5 m). **B**, *Senegalinium dilwynense* (74, AW 20 m). **C**, *Spinidinium bellum* (74, AW 20 m). **D**, **E**, representatives of *Phelodinium* spp. (74, AW 20 m). **F**, *Palaeocystodinium* cf. *lidiae* (21, LN 3.3 m). **G**, *Palaeocystodinium* cf. *minor* (26, LN 3.7 m). **H**, *Senegalinium* sp. (75, AW ~20–22 m). **I**, **J**, *Cerodinium* cf. *kangiliense* (60, AW 3.6 m). **K**, **L**, *Diconodinium* cf. *sinense* (29, LN 3.9 m). **M**, *Achomosphaera* sp. (29, LN 3.9 m). **N**, *Hafniasphaera* sp. (78, AW 21.8 m). **O**, *Pterodinium* cf. *ayachense* (90, OR 2.3 m). **P**, **Q**, *Leptodinium* sp. (87, AW 33 m). **R**, *Spiniferites* sp. B (26, LN 3.7

m). **S**, *Achomosphaera* cf. *minor* (64, AW 9.1 m). **T**, *Spiniferites* sp. A (33, LN 4.3 m). **U**, *Spiniferites* cf. sp. of Oboh-Ikuenobe et al. (2017) exhibiting distally ragged tetra- and multifurcate processes (33, LN 4.3 m). **V**, *Nematosphaeropsis* cf. *philippotii* (90, OR 2.3 m). **W**, *Spiniferites*–*Nematosphaeropsis* sp. (29, LN 3.9 m).



Supplementary Fig. 2. Bright-field photomicrographs of selected dinoflagellate cysts. Specimen samples and positions in brackets. Section abbreviations: AW, Appian Way; LN, Lynnwood; OR, Oyster River. **A, B**, *Danea* cf. *heterospinosa* (62, AW 6.6 m). **C, D**, *Danea* cf. *impages* (33, LN 4.3 m). **E**, *Danea*? sp. (53, LN 43.5 m). **F**, *Cordosphaeridium* sp. A (75, AW ~20–22 m). **G, H**, *Eocladopyxis*? sp. (60, AW 3.6 m). **I**, *Cordosphaeridium* sp. B (53, LN 43.5 m). **J**, *Apteodinium* cf. *fallax* (77, AW

~20–22). **K**, *Apteodinium* cf. *cornutum* (23, LN 3.4 m). **L**, *Batiacasphaera* cf. *solida* (67, AW 12.4 m). **M**, **N**, *Stephodinium*? sp. (90, OR 2.3 m). **O**, representative of *Impagedinium* spp. (88, OR 0.6 m). **P**, **Q**, *Impagedinium*? sp. (32, LN 4.2 m). **R**, **S**, Cyst Type A (90, OR 2.3 m). **T**, Cyst Type B (31, LN 4.1 m). **U**, Cyst Type C (53, LN 43.5 m). **V**, **W**, *Tanyosphaeridium* sp. (88, OR 0.6 m). **X**, *Sentusidinium granulosa* (77, AW ~20–22).



Supplementary Fig. 3. Bright-field photomicrographs of selected marine and terrestrial palynomorphs. Specimen samples and positions in brackets. Section abbreviations: AW, Appian Way; LN, Lynnwood; OR, Oyster River. **A**, **B**, *Cymatiosphaera* sp. (88, OR 0.6 m). **C**, representative chorate acritarch (90, OR 2.3 m). **D**, Coronate Palynomorph Type A (90, OR 2.3 m). **E**, Coronate Palynomorph Type B (77, AW ~20–22 m). **F**, Kalyptate Palynomorph Type B (21, LN 3.3 m). **G**, Kalyptate Palynomorph Type A (90, OR 2.3 m). **H**, *Fromea* sp. (90, OR 2.3 m). **I**, representative of *Laevigatosporites* spp. (45, LN 21.8 m). **J**, *Stereisporites* sp. (88, OR 0.6 m). **K**, representative of *Gleicheniidites* spp. (59, AW 2.3 m). **L**, representative of *Trilobosporites* spp. (33, LN 4.3 m). **M**, *Triporopollenites* sp. (86, AW 31.5 m). **N**, *Chenopodipollis*? sp. (23, LN 3.4 m). **O**, representative of *Tricolpites* spp. (85, AW ~30–31.5 m). **P**, *Parviprojectus* sp. (30, LN 4 m). **Q**, *Tricolporites* sp. (25, LN 3.6 m). **R**, *Podocarpidites* sp. B (74, AW 20 m). **S**, representative of *Alisporites* spp. (90, OR 2.3 m). **T**, representative of *Piceapollenites* spp. (55, LN 46.5 m).

References

- Alberti, G., 1959. Zur Kenntnis der Gattung *Deflandrea* Eisenack (Dinoflag.) in der Kreide und im Alttertiär Nord- und Mitteldeutschlands. Mitteilungen aus dem Geologischen Staatsinstitut in Hamburg 28, 93–105, pls. 8–9 (in German).
- Alberti, G., 1961. Zur Kenntnis mesozoischer und alttertiärer Dinoflagellaten und Hystrichosphaerideen von Nord- und Mitteldeutschland sowie einigen anderen europäischen Gebieten. Palaeontographica,

- Abteilung A 116, 1–58, pls. 1–12 (in German).
- Anderson, R.Y., 1960. Cretaceous-Tertiary palynology, eastern side of the San Juan Basin, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Memoir 6, 1–59.
- Antolinez-Delgado, H., Oboh-Ikuenobe, F.E., 2007. New species of dinoflagellate cysts from the Paleocene of the Anambra Basin, southeast Nigeria. *Palynology* 31, 53–62.
- Artzner, D.G., Dörhöfer, G., 1978. Taxonomic note: *Lejeunecysta* nom. nov. pro. *Lejeunia* Gerlach 1961 emend. Lentin and Williams 1976—dinoflagellate cyst genus. *Canadian Journal of Botany* 56, 1381–1382.
- Awad, W.K., Oboh-Ikuenobe, F.E., 2016. Early Paleogene dinoflagellate cysts from ODP Hole 959D, Côte d'Ivoire-Ghana Transform Margin, West Africa: New species, biostratigraphy and paleoenvironmental implications. *Journal of African Earth Sciences* 123, 123–144.
- Biffi, U., Grignani, D., 1983. Peridinioid dinoflagellate cysts from the Oligocene of the Niger Delta, Nigeria. *Micropaleontology* 29, 126–145.
- Braman, D.R., 2013. Triprojectate pollen occurrence in the Western Canada Sedimentary Basin and the group's global relationships. *Royal Tyrrell Museum of Palaeontology Contribution Series* 1, 1–538.
- Bukry, D., 1976. Cenozoic silicoflagellate and coccolith stratigraphy, South Atlantic Ocean, Deep Sea Drilling Project Leg 36. Deep Sea Drilling Project, Initial Reports 35, 885–917.
- Clarke, R.F.A., Verdier, J.-P., 1967. An investigation of microplankton assemblages from the Chalk of the Isle of Wight, England. *Verhandelingen der Koninklijke Nederlandse Akademie van Wetenschappen, Afdeling Natuurkunde, Eerste Reeks* 24, 1–96, pls. 1–17.
- Clarke, R.F.A., Davey, J.R., Sarjeant, W.A.S., Verdier, J.-P., 1968. A note on the nomenclature of some Upper Cretaceous and Eocene dinoflagellate taxa. *Taxon* 17, 181–183.
- Cookson, I.C., Eisenack, A., 1958. Microplankton from Australian and New Guinea upper Mesozoic sediments. *Proceedings of the Royal Society of Victoria* 70, 19–78, pls. 1–12.
- Cookson, I.C., Eisenack, A., 1960. Microplankton from Australian Cretaceous sediments. *Micropaleontology* 6, 1–18.
- Cookson, I., Eisenack, A., 1960. Upper Mesozoic microplankton from Australia and New Guinea. *Palaeontology* 2, 243–261, pls. 37–39.
- Cookson, I.C., Eisenack, A., 1965a. Microplankton from the Dartmoor Formation, SW. Victoria. *Proceedings of the Royal Society of Victoria* 79, 133–137, pls. 16–17.
- Cookson, I.C., Eisenack, A., 1965b. Microplankton from the Paleocene Pebble Point Formation, southwestern Victoria. *Proceedings of the Royal Society of Victoria* 79, 139–146, pl. 18–19.
- Cookson, I.C., Eisenack, A., 1967. Some microplankton from the Paleocene Rivernook Bed, Victoria. *Proceedings of the Royal Society of Victoria* 80, 247–257, pls. 39–42.
- Cookson, I.C., Eisenack, A., 1970a. Cretaceous microplankton from the Eucla Basin, Western Australia. *Proceedings of the Royal Society of Victoria* 83, 2–4.
- Cookson, I.C., Eisenack, A., 1970b. Die Familie der Lecaniellaceae n. fam.—fossile Chlorophyta, Volvocales? *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte* 6, 321–325 (in German).
- Cookson, I.C., Eisenack, A., 1974. Mikroplankton aus australischen mesozoischen und tertiären Sedimenten. *Palaeontographica, Abteilung B* 148, 44–93, pls. 20–29 (in German).
- Damassa, S.P., 1979a. Eocene dinoflagellates from the Coastal Belt of the Franciscan Complex, northern California. *Journal of Paleontology* 53, 815–840, pls. 1–8.
- Damassa, S.P., 1979. Danian dinoflagellates from the Franciscan Complex, Mendocino County, California. *Palynology* 3, 191–207.
- Davey, R.J., 1969. The evolution of certain Upper Cretaceous hystrichospheres from South Africa. *Palaeontologia Africana* 12, 25–51.
- Davey, R.J., Williams, G.L., 1966a. The genera *Hystrichosphaera* and *Achomosphaera*. In: Davey, R.J., Downie, C., Sarjeant, W.A.S., Williams, G.L. (Eds.), *Studies on Mesozoic and Cainozoic dinoflagellate cysts*. *Bulletin of the British Museum (Natural History), Geology, Supplement* 3, pp. 28–52, pls. 1–5, 9.
- Davey, R.J., Williams, G.L., 1966b. V. The genus *Hystrichosphaeridium* and its allies. In: Davey, R.J.,

- Downie, C., Sarjeant, W.A.S., Williams, G.L. (Eds.), Studies on Mesozoic and Cainozoic dinoflagellate cysts. Bulletin of the British Museum (Natural History), Geology, Supplement 3, pp. 53–106, pls. 3–12.
- Davey, R. J., Downie, C., Sarjeant, W.A.S., Williams, G.L., 1966. VII. Fossil dinoflagellate cysts attributed to *Baltisphaeridium*. In: Davey, R.J., Downie, C., Sarjeant, W.A.S., Williams, G.L. (Eds.), Studies on Mesozoic and Cainozoic dinoflagellate cysts. Bulletin of the British Museum (Natural History), Geology, Supplement 3, pp. 157–175, pls. 2, 3, 8–11.
- de Coninck, J., 1968. Dinophyceae et Acritarcha de l'Yprésien du sondage de Kallo. Mémoires de l'Institut Royal des Sciences Naturelles de Belgique 161, 1–67, pls. 1–17 (in French).
- Deflandre, G., 1936. Microfossiles des silex crétacés. Première partie. Généralités. Flagellés. Annales de Paléontologie 25, 151–191 (also labelled 3–43), pls. 11–20 (also labelled pls. 1–10) (in French).
- Deflandre, G., 1937. Microfossiles des silex crétacés. Deuxième partie. Flagellés *incertae sedis*. Hystrichosphaeridés. Sarcodinés. Organismes divers. Annales de Paléontologie 26, 51–103 (also labelled 3–55), pls. 11–18 (also labelled pls. 8–15) (in French).
- Deflandre, G., 1947a. Sur une nouvelle hystrichosphère des silex crétacés et sur les affinités du genre *Cannosphaeropsis* O. We. Comptes rendus Hebdomadaires des Séances de l'Académie des Sciences 224, 1574–1576 (in French).
- Deflandre, G., 1947b. Sur quelques micro-organismes planctoniques des silex Jurassiques. Bulletin de l'Institut océanographique de Monaco 921, 1–10 (in French).
- Deflandre, G., Cookson, I. C., 1955. Fossil microplankton from Australian late Mesozoic and Tertiary sediments. Australian Journal of Marine and Freshwater Research 6, 242–313, pls. 1–9.
- Drugg, W.S., 1964. *Glyphanodinium*, a new dinoflagellate genus from the Paleocene of California. Proceedings of the Biological Society of Washington 77, 237–240.
- Drugg, W.S., 1967. Palynology of the upper Moreno Formation (Late Cretaceous-Paleocene) Escarpado Canyon, California. Palaeontographica, Abteilung B 120, 1–71, pls. 1–9.
- Drugg, W.S., 1970. Some new genera, species, and combinations of phytoplankton from the lower Tertiary of the Gulf Coast, U.S.A. Proceedings of the North American Paleontological Convention, Chicago, September 1969, Part G, 809–843.
- Duxbury, S., 1980. Barremian phytoplankton from Speeton, east Yorkshire. Palaeontographica, Abteilung A 173, 107–146, pls. 1–13.
- Eaton, G.L., 1976. Dinoflagellate cysts from the Bracklesham Beds (Eocene) of the Isle of Wight, southern England. Bulletin of the British Museum (Natural History), Geology 26, 227–332, pls. 1–21.
- Ehrenberg, C.G., 1837. Über das Massenverhältniss der jetzt lebenden Kiesel-Infusorien und über ein neues Infusorien-Conglomerat als Polierschiefer von Jastraba in Ungarn. Königlich Akademie der Wissenschaften zu Berlin, Abhandlungen, 1836 1, 109–135, pls. 1–2 (in German).
- Eisenack, A., 1958. Mikrop plankton aus dem norddeutschen Apt, nebst einigen Bemerkungen über fossile Dinoflagellaten. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 106, 383–422, pls. 21–27 (in German).
- Evitt, W.R., Clarke, R.F.A., Verdier, J.-P., 1967. Dinoflagellate studies III. *Dinogymnium acuminatum* n. gen., n. sp. (Maastrichtian) and other fossils formerly referable to *Gymnodinium* Stein. Stanford University Publications, Geological Sciences 10, 1–27, pls. 1–3.
- Evitt, W.R., Damassa, S.P., Albert, N.R., 1998. A tiger by the tail: The exophragm of the Cretaceous–Paleocene dinoflagellate *Palaeoperidinium* and its implications. Palynology 22, 1–55.
- Fensome, R.A., Williams, G.L., 2005. Scotian Margin PalyAtlas, Version 1. Geological Survey of Canada, Open File 4677.
- Fensome, R.A., Williams, G.L., MacRae, R.A., 2009. Late Cretaceous and Cenozoic fossil dinoflagellates and other palynomorphs from the Scotian Margin, offshore eastern Canada. Journal of Systematic Palaeontology 7, 1–79.
- Fensome, R.A., Williams, G.L., Wood, S.E.L., Riding, J.B., 2019. A review of the areoligeracean dinoflagellate cyst *Cyclonephelium* and morphologically similar genera. Palynology 43, 1–71.

- Gerlach, E., 1961. Mikrofossilien aus dem Oligozän und Miozän Nordwestdeutschlands, unter besonderer Berücksichtigung der Hystrichosphaeren und Dinoflagellaten. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 112, 143–228, pls. 25–29 (in German).
- Gocht, H., 1970. Dinoflagellaten-Zysten aus einem Geschiebefeuerstein und ihr Erhaltungszustand. Neues Jahrbuch für Geologie und Paläontologie, Monatshefte 3, 129–140 (in German).
- Goodman, D.K., Witmer, R.J., 1985. Archeopyle variation and paratabulation in the dinoflagellate *Diphyes colligerum* (Deflandre & Cookson 1955) Cookson 1965. Palynology 9, 61–84.
- Górka, H., 1963. Coccolithophoridés, dinoflagellés, hystrichosphaeridés et microfossiles *incertae sedis* du Crétacé supérieur de Pologne. Acta Palaeontologica Polonica 8, 3–90, pls. 1–11 (in French).
- Guédé, K.É., Slimani, H., Louwye, S., Asebriy, L., Toufiq, A., Ahmamou, M., Hassani, I.-E.E.A.E., Digbehi, Z.B., 2014. Organic-walled dinoflagellate cysts from the Upper Cretaceous–lower Paleocene succession in the western External Rif, Morocco: New species and new biostratigraphic results. Geobios 47, 291–304.
- Hansen, J.M., 1977. Dinoflagellate stratigraphy and echinoid distribution in Upper Maastrichtian and Danian deposits from Denmark. Bulletin of the Geological Society of Denmark 26, 1–26.
- Harland, R., 1979. *Agerasphaera* nov. gen., an ‘*Eisenackia*’-like dinoflagellate cyst from the Thanet Sands (Paleocene) of southeast England. Review of Palaeobotany and Palynology 28, 27–35.
- He Chengquan, 1991. Late Cretaceous-early Tertiary microphytoplankton from the western Tarim Basin in southern Xinjiang, China. Nanjing Institute of Geology and Palaeontology, Academia Sinica, 1–235, pls. 1–65 (in Chinese).
- He Chengquan, Wang Kede, 1990. Eocene dinoflagellates from the southwestern continental shelf basin of the East China Sea. Acta Micropalaeontologica Sinica 7, 403–426, pls. 1–4.
- Head, M.J., Norris, G., Mudie, P.J., 1989. New species of dinocysts and a new species of acritarch from the upper Miocene and lowermost Pliocene, ODP Leg 105, Site 646, Labrador Sea. In: Srivastava, S.P., Arthur, M.A., Clement, B. et al. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results 105, 453–466.
- Helby, R.J., 1987. *Muderongia* and related dinoflagellates of the latest Jurassic to Early Cretaceous of Australasia. In: Jell, P.A. (Ed.), Studies in Australian Mesozoic palynology. Memoir of the Association of Australian Palaeontologists 4, pp. 297–336.
- Hultberg, S.U., 1985. Systematic paleontology. In: Hultberg, S.U. (Ed.), Dinoflagellate studies of the upper Maastrichtian and Danian in southern Scandinavia (Publ. PhD thesis). University of Stockholm, Stockholm, Sweden, pp. 104–189.
- Hultberg, S.U., Malmgren, B.A., 1985. Quantitative biostratigraphy based on upper Maastrichtian dinoflagellates and planktonic foraminifera from southern Scandinavia. In: Hultberg, S.U. (Ed.), Dinoflagellate studies of the upper Maastrichtian and Danian in southern Scandinavia (Publ. PhD thesis). University of Stockholm, Stockholm, Sweden, pp. 33–55.
- Jan du Chêne, R., 1988. Étude systématique des kystes de dinoflagellés de la Formation des Madeleines (Danian du Sénégal). Cahiers de Micropaléontologie, Centre Nationale de la Recherche Scientifique 2, 147–172, pls. 1–28 (in French).
- Jan du Chêne, R., Adediran, S.A., 1984. Late Paleocene to early Eocene dinoflagellates from Nigeria. Cahiers de Micropaléontologie, Centre Nationale de la Recherche Scientifique 3, 5–38, pls. 1–25.
- Klumpp, B., 1953. Beitrag zur Kenntnis der Mikrofossilien des mittleren und oberen Eozän. Palaeontographica, Abteilung A 103, 377–406, pls. 16–20 (in German).
- Lejeune-Carpentier, M., 1940. L’étude microscopique des silex. Systématique et morphologie des “tubifères”. (Huitième note). Annales de la Société géologique de Belgique 63, B216–B236 (in French).
- Lejeune-Carpentier, M., 1942. L’étude microscopique des silex. Péridiniens nouveaux ou peu connus. (Dixième note). Annales de la Société géologique de Belgique 65, B181–B192, 3 pls.
- Lejeune-Carpentier, M., Sarjeant, W.A.S., 1981. Restudy of some larger dinoflagellate cysts and an acritarch from the Upper Cretaceous of Belgium and Germany. Annales de la Société géologique de Belgique 104, 1–39.

- Lentin, J.K., Williams, G.L., 1973. Fossil dinoflagellates: index to genera and species. Geological Survey of Canada, Paper 73-42, 1–176.
- Lentin, J.K., Williams, G.L., 1976. A monograph of fossil peridinioid dinoflagellate cysts. Bedford Institute of Oceanography, Report Series BI-R-75-16, 237 pp.
- Lentin, J.K., Williams, G.L., 1980. Dinoflagellate provincialism with emphasis on Campanian peridiniaceans. American Association of Stratigraphic Palynologists, Contributions Series 7, 47 pp.
- Lentin, J.K., Williams, G.L., 1987. Status of the fossil dinoflagellate genera *Ceratiopsis* Vozzhennikova 1963 and *Cerodinium* Vozzhennikova 1963 emend. *Palynology* 11, 113–116.
- Lucas-Clark, J., 2006. Small peridinioid dinoflagellate cysts from the Paleocene of South Carolina, U.S.A. *Palynology* 30, 183–210.
- Mantell, G.A., 1854. The medals of creation; or, first lessons in geology and the study of organic remains. 2nd edition. Henry G. Bohn, London. 930 pp., pls. 1–6 (in two volumes).
- Manum, S., Cookson, I.C., 1964. Cretaceous microplankton in a sample from Graham Island, arctic Canada, collected during the second "[sic]Fram" expedition (1898–1902). With notes on microplankton from the Hassel Formation, Ellef Ringnes Island. *Norske Videnskaps-Akademi i Oslo, I. Matematisk-Naturvidenskapelig Klasse, Skrifter, Ny Serie* 17, 1–36, pls. 1–7.
- Matsuoka, K. 1983. A new dinoflagellate cyst (*Danea heterospinosa*) from the Eocene of central Java, Indonesia. *Review of Palaeobotany and Palynology* 40, 115–126.
- Mindell, R.A., Stockey, R.A., Beard, G., 2006. Anatomically preserved staminate inflorescences of *Gynoplatananthus oysterbayensis* gen. et sp. nov. (Platanaceae) and associated pistillate fructifications from the Eocene of Vancouver Island, British Columbia. *International Journal of Plant Sciences* 167, 591–600.
- Morgenroth, P., 1966. Mikrofossilien und Konkretionen des nordwesteuropäischen Untereozäns. *Palaeontographica, Abteilung B* 119, 1–53, pls. 1–11 (in German).
- Morgenroth, P., 1968. Zur Kenntnis der Dinoflagellaten und Hystrichosphaeridien des Danien. *Geologisches Jahrbuch* 86, 533–577 (in German).
- Nichols, D.J., 2002. Palynology and palynostratigraphy of the Hell Creek Formation in North Dakota: A microfossil record of plants at the end of Cretaceous time. *Geological Society of America Special Paper* 361, 393–456.
- Nøhr-Hansen, H., 1994. Dinoflagellate cyst biostratigraphy of the Upper Cretaceous black mudstones between Niaqornat and Ikorfat of the north coast of Nuussuaq West Greenland. *Grønlands Geologiske Undersøgelse, Open File Series* 94/14, 1–24.
- Nøhr-Hansen, H., Heilmann-Clausen, C., 2001. *Cerodinium kangiliense* n. sp. and *Senegalinium iterlaense* n. sp.—two new stratigraphically important Paleocene species from West Greenland and Denmark. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 219, 153–170.
- Norton, N.J., 1965. Three new species of *Aquilapollentia* from the Hell Creek Formation, Garfield County, Montana. *Pollen et Spores* 7, 135–143.
- Oboh-Ikuenobe, F.E., Antolinez-Delgado, H., Awad, W.K., 2017. Dinoflagellate cyst assemblages, biostratigraphy and paleoenvironment of a Paleocene–early Eocene sedimentary succession in the northern Niger Delta Basin: Comparison with low, mid and high latitude regions. *Palaeogeography, Palaeoclimatology, Palaeoecology* 481, 29–43.
- Peyrot, D., 2011. Late Cretaceous (late Cenomanian–early Turonian) dinoflagellate cysts from the Castilian Platform, northern Spain. *Palynology* 35, 267–300.
- Quattrocchio, M.E., Sarjeant, W.A.S., 2003. Dinoflagellates from the Chorrillo Chico Formation (Paleocene) of southern Chile. *Ameghiniana* 40, 129–153.
- Rosignol, M., 1964. Hystrichosphères du Quaternaire en Méditerranée orientale, dans les sédiments Pléistocènes et les boues marines actuelles. *Revue de Micropaléontologie* 7, 83–99 (in French).
- Sarjeant, W.A.S., 1970. The genus *Spiniferites* Mantell, 1850 (Dinophyceae). *Grana* 10, 74–78.
- Sarjeant, W.A.S., 1981. A restudy of some dinoflagellate cyst holotypes in the University of Kiel collections. II. The Eocene holotypes of Barbara Klumpp (1953); with a revision of the genus *Cordosphaeridium* Eisenack, 1963. *Meyniana* 33, 97–132, pls. 1–6.

- Sarjeant, W.A.S., 1984. A restudy of some dinoflagellate cyst holotypes in the University of Kiel collections. V. The Danian (Palaeocene) holotypes of Walter Wetzel (1952, 1955). *Meyniana* 36, 121–171.
- Sarjeant, W.A.S., 1985. A restudy of some dinoflagellate cyst holotypes in the University of Kiel collections: VI. Late Cretaceous dinoflagellate cysts and other palynomorphs in the Otto Wetzel collection. *Meyniana* 37, 129–185.
- Shae Cheng-Long, 1999. Eocene dinoflagellate cysts of Taiwan. *Taiwania* 44, 155–201.
- Sims, P.A., 1998. The early history of the Biddulphiales. I. The genus *Medlinia* gen. nov. *Diatom Research* 13, 337–374.
- Singh, C., 1971. Lower Cretaceous microfloras of the Peace River area, northwestern Alberta. *Research Council of Alberta, Bulletin* 28, 542 pp.
- Slimani, H., 2003. A new genus and two new species of dinoflagellate cysts from the Upper Cretaceous of the Maastrichtian type area and Turnhout (northern Belgium). *Review of Palaeobotany and Palynology* 126, 267–277.
- Sluijs, A., Brinkhuis, H., Williams, G.L., Fensome, R.A., 2009. Taxonomic revision of some Cretaceous–Cenozoic spiny organic-walled peridiniacean dinoflagellate cysts. *Review of Palaeobotany and Palynology* 154, 34–53.
- Stanley, E.A., 1965. Upper Cretaceous and Paleocene plant microfossils and Paleocene dinoflagellates and hystrichosphaerids from northwestern South Dakota. *Bulletins of American Paleontology* 49, 179–384.
- Steeman, T., De Weirtdt, J., Smith, T., De Putter, T., Mees, F., Louwye, S., 2020. Dinoflagellate cyst biostratigraphy and palaeoecology of the early Paleogene Landana reference section, Cabinda Province, Angola. *Palynology* 44, 280–309.
- Stover, L.E., Evitt, W.R., 1978. Analyses of pre-Pleistocene organic-walled dinoflagellates. *Stanford University Publications, Geological Sciences* 15, 300 pp.
- Stover, L.E., Hardenbol, J., 1994. Dinoflagellates and depositional sequences in the Lower Oligocene (Rupelian) Boom Clay Formation, Belgium. *Bulletin de la Société belge de géologie* 102, 5–77, pls. 1–13 (Cover date 1993, issue date 1994).
- Wetzel, O., 1933. Die in organischer Substanz Erhaltenen Mikrofossilien des baltischen Kreide-Feuersteins mit einem sediment-petrographischen und stratigraphischen Anhang. *Palaeontographica, Abteilung A* 77, 141–187, pls. 1–2 (in German).
- Wetzel, O., 1952. Beitrag zur Kenntnis des dan-zeitlichen Meeresplanktons. *Geologisches Jahrbuch* 66, 391–419 (in German).
- Williams, G.L., Downie, C., 1966. V. Further dinoflagellate cysts from the London Clay. In: Davey, R.J., Downie, C., Sarjeant, W.A.S., Williams, G.L. (Eds.), *Studies on Mesozoic and Cainozoic dinoflagellate cysts. Bulletin of the British Museum (Natural History), Geology, Supplement* 3, pp. 215–236, pls. 24–26.
- Witt, O.N., 1885. Über den Polierschiefer von Archangelsk-Kurojedowo im Gouv. Simbirsk. *Verhandlungen der Russisch-kaiserlichen Mineralogischen Gesellschaft zu St. Petersburg, Series II* 22, 137–177, pls. 6–12 (in German).
- Wrenn, J.H., Hart, G.F., 1988. Paleogene dinoflagellate cyst biostratigraphy of Seymour Island, Antarctica. *Geological Society of America, Memoir* 169, 321–447.

Appendix 1.B. Table 1. Palynological sample data | Specimen counts, concentrations, dinoflagellate cyst diversity and taxa richness

Sample No.	USGS ID No.	Cystic Bag Per Section	Dinoflagellate Cyst Zone	Diversity Indices										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa										Taxa									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Table 2. Palynological sample data | Dinoflagellate cyst and pollen and spore relative abundances

[illegible]

Appendix 1.C. Global distribution of selected dinoflagellate cyst taxa for the latest Cretaceous–earliest Paleogene identified in the Oyster Bay Formation

We present a literature review of the reported geographic distributions of selected dinoflagellate cysts established as K/Pg interval indicator taxa with presence in the Oyster Bay Formation, Vancouver Island, British Columbia, Canada. Entries are provided for dinoflagellate cyst species selected based on known K/Pg boundary constraints or prevalence in proximity to the K/Pg boundary. Records prior to 2004 were retrieved with the assistance of the PALYNODATA online database (Palynodata Inc. and White, 2008). A record is herein defined as an original reported occurrence of a taxon as it relates to a given geological formation or regional rock package within the scope of a published study. Nominal species reports accompanied by photomicrographs have their publication dates in bold whereas solely nominal species reports have their publication dates in regular typeface (e.g., Slimani, **2000**, 2001). Nomenclature follows that of Fensome et al. (2019). At least three references are cited for the occurrence of a taxon in a given state, country, or region from where more than three studies have been published.

Systematic Paleontology

Division Dinoflagellata (Bütschli, 1885) Fensome et al., 1993

Class Dinophyceae Pascher, 1914

Genus *Apteodinium* (Eisenack, 1958) Lucas-Clark, 1987

Apteodinium fallax (Morgenroth, 1968) Stover and Evitt, 1978

Occurrence. Reports of *Apteodinium fallax* range from strata of Late Cretaceous age (upper Campanian: ?Shaozhi Mao and Norris, 1984; Tea-Yassi et al., 1999) to middle Paleocene age (Selandian: Morton et al., 1988; Slimani et al., **2016**). The species is known from the upper Maastrichtian strata of the Lechówka succession, Poland (Machalski et al., **2016**), the Ouled Haddou section, Morocco (Slimani et al., **2010**) and the Danian strata of Denmark (Morgenroth, **1968**), although its greatest prevalence has been documented from across K/Pg boundary intervals (Turkey: Açikalin et al., 2015; Morocco: Chakir et al., **2020**; Jbari et al., **2020**; Tunisia: Brinkhuis and Zachariasse, 1988; M'Hamdi et al., **2013**; Egypt: Soliman and Slimani, **2019**) and strata of Danian age (Denmark: Jan du Chêne et al., **1986**; Morocco: Guédé et al., **2014**; Slimani et al., **2016**) (Supplementary Fig. 1).

Remarks. Save for antapical horn expression, *Apteodinium fallax* bears considerable morphological similarity to *Kenleyia nuda* de Coninck, 1968, a species postulated by several workers (Brinkhuis and Zachariasse, 1988; Damassa, 1988) to be conspecific with *Carpatella cornuta*. Specimens observed

within the Oyster Bay Formation have reduced apical horn expression, hence their assignment to *A. cf. fallax*.

Genus ***Areoligera*** (Lejeune-Carpentier, 1938) Williams and Downie, 1966

Areoligera volata Drugg, 1967

Occurrence. Reports of *Areoligera volata* are limited to the Northern Hemisphere having their earliest occurrence in upper Campanian strata (British Columbia: McLachlan et al., **2018**; Austria: Soliman et al., 2009; Mohamed and Wagreich, 2013; Italy: Torricelli and Amore, **2003**) with their highest range top reported from the lowermost Eocene strata of New Jersey (Sluijs et al., 2018) and more questionably Austria (Mohamed and Wagreich, 2013), as the authors note concern regarding localized reworking of Paleocene sediments. Conversely, numerous studies have documented concrete range tops for *A. volata* in strata of late Paleocene age (late Selandian: Amano and Kurita, 2020; Thanetian: Schumacker-Lambry, **1977**; Jain and Garg, **1986**; Cavagnetto and Guerrero, 1999; Mehrotra and Singh, **2003**; Rabbani et al., 2015). Most Cretaceous accounts are known from upper Maastrichtian strata (Netherlands: Schiøler et al., 1997; Germany: Kirsch, **1991**; Morocco: Slimani et al., 2016; Israel: Eshet et al., 1994; Russia: Lebedeva et al., 2013; India: Jain, **1978**; Mehrotra and Sarjeant, **1987**), although the highest frequency of occurrences have been reported from across K/Pg boundary intervals (New Jersey: Vellekoop et al., **2019b**; Gulf of Guinea: Masure et al., **1998**; Netherlands: Brinkhuis and Schiøler, **1996**; Germany: Egger and Mohamed, **2010**; Morocco: Chakir et al., **2020**; Jbari et al., 2020; Tunisia: Brinkhuis et al., 1998) and strata of Danian age (Belgium: e.g., Schumacker-Lambry and Chateauneuf, **1976**; Slimani, **1994**; Slimani et al., 2011; California: Drugg, **1967**; Georgia: Edwards, **2001**; Denmark: Hansen, 1977; Germany: Köthe, **1991**; Senegal: Bellion et al., **1985**; Egypt: Soliman and Slimani, **2019**; China: Xiaoqiao Wan et al., 2014) (Supplementary Fig. 1).

Remarks. *Areoligera volata*, characterized by marginate trabecular process complexes and pronounced antapical lobes, has been observed within a plexus of gradation toward end members corresponding to *Areoligera coronata* (Wetzel, 1933b) Lejeune-Carpentier, 1938 within the Oyster Bay Formation as well as from the upper Campanian Northumberland Formation on Hornby Island, British Columbia (McLachlan et al., 2018). *Areoligera coronata* is a longer ranging species with records spanning from the Upper Cretaceous (e.g., lower Campanian: Kirsch 1991) to lower Miocene (Burdigalian: Helenes and Cabrera, 2003). The occurrence of a form assigned to *Areoligera* sp. cf. *A. coronata* is reported by Lamolda and Shaozhi Mao (1999) from the upper Cenomanian–lower Turonian strata of northern Spain, but no material was figured. Similar transitional specimens between *A. volata* and *A. coronata* have also been recorded from Sweden as *A. coronata* (de Coninck, 1975).

Genus ***Danea*** (Morgenroth, 1968) Drugg, 1970

Danea californica (Drugg, 1967) Damassa, 1979a

Occurrence. *Danea californica* has a global distribution almost exclusively constrained to strata of Danian age. Within North America, the species has been well documented (California: Drugg, **1967**; Damassa, **1979i**; Texas: ~~Evvitt, 1973~~ [misidentified *Carpatella cornuta*, pl. 1, figs. 12–14]; Keller et al., 2007; Prauss, 2009; New Jersey: e.g., Habib and Saeedi, 2007; Landman et al., **2007**; Esmeray-Senlet et al., 2017; Maryland: Edwards et al., **1984**; Whitney, **1984**; Virginia: Gibson et al., 1980; Edwards et al., **1984**; Baja California: Helenes, **1984**; Helenes and Téllez-Duarte, **2002**; South Carolina: e.g., Edwards, **1998**, 2000; Van Pelt et al., 2000; Lucas-Clark, 2006; Georgia: e.g., Edwards, 1980; Habib and Miller, 1989; Moshkovitz and Habib, **1993**; Missouri: Frederiksen et al., 1982; Dastas et al., **2014**; Alabama: e.g., Damassa, **1984**; Habib et al., 1992, 1996) with reports extending into South America (Guatemala: Fourcade et al., 1997; Venezuela: Pocknall et al., 2001; Pocknall and Erlich, 2020; Yepes, 2001; ~~Brasil: de Oliveira Alves, 2019~~ [misidentified *Kenleyia*? sp., fig. 6A]; ?offshore Brasil: Premaor et al., **2018**; Guerstein and Daners, **2004**; Argentina: e.g., Barreda et al., 2012; Clyde et al., 2014; Vellekoop et al., **2017**; Woelders et al., 2017; Guler et al., 2019; González Estebenet et al., 2021) and across the Atlantic (offshore Uruguay: Guerstein et al., 2005; offshore eastern Canada: Williams and Bujak, 1977; Barss et al., 1979; North Atlantic: Diederix et al., 1972; Gulf of Guinea: Masure et al., **1998**). Beyond the Americas, records are widespread in Europe (North Sea: Köthe, **2007**, **2012**; Vieira et al., 2020b; Sweden: e.g., Kjellström and Hansen, 1981; Hultberg, **1986**; de Coninck, **1975**; Denmark: e.g., Hansen, **1977**; Thomsen and Heilmann-Clausen, **1985**; FitzPatrick et al., **2017**; Belgium: e.g., ~~Wilson, 1971~~ [misidentified *Carpatella cornuta*, pl. 1, fig. 13]; Slimani, 2001; Slimani et al., **2011**; Spain: de Coninck and Smit, **1982**; France: e.g., Van Stuijvenberg, 1980; Foucher and Masure, 1983; Cavagnetto and Tambareau, **1998**; Germany: Morgenroth, **1968**; Köthe, 1991; Egger and Mohamed, **2010**; Netherlands: Herngreen et al., **1998**; Brinkhuis et al., 2000; Austria: Kuhn and Kirsch, **1992**; Mohamed et al., **2012**, **2013**; Romania: Țabără et al., **2017**; Ukraine: Portnyagina, 1971; Andreeva-Grigorovich and Suprun, 2016) and Asia (Turkey: Erkmén and Sadek, **1981**; Açikalin et al., **2015**; Russia: e.g., Vasilyeva, 1990, **2017**; Sharafutdinova, 1992; Amon et al., 2003; Vasilyeva, 2003; Aleksandrova et al., 2011; Andreeva-Grigorovich et al., **2011**; Vasilyeva and Musatov, 2012; Shcherbinina et al., 2014; Iran: Mohsen and Ghasemi-Nejad, 2008; Beiranvand et al., 2014; Zarei and Ghasemi-Nejad, 2015; India: e.g., Raju et al., 1995; Garg et al., **2006**; Mehrotra and Singh, **2003**; Prasad and Pundir, 2020; China: He Chengquan, **1991**; Guo Xianyu et al., 2008; Xiaoqiao Wan et al., 2014), with many African studies having reported the species (Tunisia: e.g., Brinkhuis and Zachariasse, **1988**; Brinkhuis and Leereveld, **1988** [image *redux* Brinkhuis and Zachariasse, **1988**]; Molina et al., 2006; M’Hamdi et al., **2013**; Morocco: e.g., Slimani et al., 2012; Slimani and Toufiq, **2013**; Guédé et al., 2014; Jbari et al., **2020**; Egypt: Berggren et al., 2012; Soliman and Slimani, **2019**; Mohamed et al., **2019**; Soliman and Fensome, 2019; Senegal: Bellion et al.,

1985; Nigeria: e.g., Umeji and Nwajide, **2007**; Umeji and Edet, **2008**; Durugbo, **2016**; Lucas and Osezele, **2017**; Cameroon: Kenfack et al., **2012**; Gulf of Guinea: René et al., **2012**; Awad and Oboh-Ikuenobe, **2016**; Sánchez-Pellicer et al., **2017**). In the Southern Hemisphere, specimens have also been noted from offshore Tasmania (Williams et al., **2004**) and Antarctica (Elliot et al., 1994; Bowman et al., 2016; Scasso et al., **2020**) with coeval occurrences in New Zealand (e.g., Ferrow et al., 2011; Raine and Schiøler, 2012; Willumsen, **2012**). Reported occurrences beyond the Danian are limited, known only from isolated accounts assigned to younger Paleocene strata (Alabama and Georgia: Edwards, 1980; Gulf of Mexico: Elsie and Crabaugh, 2001; offshore eastern Canada: Fensome et al., 2008, **2009**; Scotland: Morton et al., 1988; Denmark: Powell et al., **1992**; Pakistan: Köthe et al., 1988). The report of Kasiński et al. (2020) from the Selandian of Russia is misidentified [*Spongodinium?* sp. fig. 8G]. Eocene reports have either been attributed to reworking (Austria: Mohamed and Wagneich, **2013**) or are highly questionable (Hungary: Kedves, 1992).

Genus ***Deflandrea*** (Eisenack, 1938) Stover, 1973

Deflandrea galeata (Lejeune-Carpentier, 1942) Lejeune-Carpentier and Sarjeant, 1981

Occurrence. A specimen of *Deflandrea galeata* was first photomicrographed by Wetzel (**1933a**) from ‘Senonian’ to Danian-aged fintstones of northern Germany which he attributed to *Peridinium* cf. *claudicans* as noted by Lejeune-Carpentier (1942). Lejeune-Carpentier (1942) formally described the species from chalks of equivalent age from Belgium in addition to specimens from the original O. Wetzel collection. Records in upper Maastrichtian strata are most prevalent in the Northern Hemisphere (Greenland: Nøhr-Hansen, **1994**; Labrador–Baffin Seaway: Sønderholm et al., 2003; Fensome et al., **2016**; U.S. Gulf Coast: Larina et al., **2016**; Witts et al., 2018; Arkansas: Dastas & Chamberlain Jr. **2021**; New Jersey: Aurisano, **1989**; Maryland: Landman et al., **2004a**; South Carolina: Habib and Miller, 1989; Atlantic: Norris and Firth, 2002; North Sea: Schiøler and Wilson, **1993**; Denmark: Hansen 1979a, b; Surlyk et al., 2013; Netherlands: Herngreen et al., **1986**; Schiøler et al., 1997; Germany: Kirsch, **1991**; Italy: Roncaglia and Corradini **1997**; Romania: Țabără and Slimani, **2017**; Țabără et al., **2017**; Poland: Machalski et al., **2016**; Russia: Aleksandrova and Zaporozhets, 2008b; Lebedeva et al., 2013; Kazakhstan: Vasilyeva and Levina, **2007**; Morocco: Guédé et al., **2014**; Slimani et al., 2016) with occurrences having also been reported from K/Pg boundary intervals (New Jersey: Landman et al., **2007**; Vellekoop et al., **2019b**; Greenland: Nøhr-Hansen, **1996**; Belgium: Slimani, **2001**; Slimani et al., **2011**; Morocco: Chakir et al., **2020**; Jbari et al., **2020**; Tunisia: M’Hamdi et al., 2013; Vellekoop et al., 2015; Egypt: Soliman and Slimani, **2019**) and exclusively Danian strata (Alabama: Moshkovitz and Habib, 1993; Missouri: Dastas et al., **2014**; Morocco: Slimani et al., **2010**; Russia: Aleksandrova et al., **2012**). In the Southern Hemisphere, the species is present in the upper Maastrichtian strata of New Zealand

(Pocknall et al., **1988**; Willumsen, **2011**; Raine and Schiøler, 2012), the upper Maastrichtian–Danian strata of Argentina (e.g., Papú et al., **1999**; Prámparo and Papú, **2006**; Vellekoop et al., **2017**; Guler et al., **2019**; González Estebenet et al., 2021) and possibly in proximity to the K/Pg boundary in Chile (Sanchez et al., 2010).

Genus ***Eisenackia*** (Deflandre and Cookson, 1955) Quattrocchio and Sarjeant, 2003

Eisenackia reticulata (Damassa, 1979b) Quattrocchio and Sarjeant, 2003

Occurrence. Recent data syntheses infer a Danian age constraint for *Eisenackia reticulata* in the Northern Hemisphere (Luterbacher et al., 2004; Williams et al., 2004). Numerous records have seen the taxon reported to span strata presumed to be of late Maastrichtian age (Firth, 1987; Bell et al., 1990) to early Thanetian age (Naeher et al., 2019; Bijl et al., 2021) with one instance as part of a broader interspecific complex (Hollis et al., 2017). However, there exists an extensive body of literature placing the species firmly within the Danian (California: Damassa, **1979b**; offshore eastern Canada: Tucholke et al., 2004; Baffin Seaway: Toxwenius, 1986; New Jersey: Vellekoop et al., **2019b**; Denmark: Heilmann-Clausen, **1985**; North Sea: e.g., Gradstein et al., **1992**; Schiøler et al., 2007; Vieira et al., **2017**, 2019, 2020b; France: Cavagnetto and Tambareau, **1998**; Cavagnetto and Guerrero, 1999; Netherlands: Brinkhuis and Schiøler, **1996**; southwestern Russia: Andreeva-Grigorovich et al., **2011**; Vasilyeva and Musatov, 2012; Shcherbinina et al., 2014; Morocco: Jbari et al., **2020**; Iran: Beiranvand et al., 2014). In the Southern Hemisphere, the species has been recorded from upper Maastrichtian successions (Tasman Plateau: Schellenberg et al., 2004; New Zealand: Strong et al., 1995; Antarctica: e.g., Askin, **1988**; Crame et al., 1991; Amenábar et al., 2014), across K/Pg boundary intervals (Australia: Alley and Clarke, **1992**; New Zealand: Willumsen, **2011**; southern Indian Ocean: Barron et al., 1989; Tocher, 1991) and into strata of Danian age (?offshore Brasil: Premaor et al., **2018**; Argentina: Guler et al., 2019; Australia: Frieling et al., **2018**; offshore Tasmania: Exon et al., 2001; Williams et al., **2004**; New Zealand: Pocknall et al., 1988; Hollis et al., 2017) with Williams et al. (**2004**) citing extension into strata of earliest Ypresian age.

Genus ***Fibradinium*** Morgenroth, 1968

Fibradinium annetorpense Morgenroth, 1968

Occurrence. Reports of *Fibradinium annetorpense* range from strata of Late Cretaceous age (Santonian: Barss et al., 1979; Campanian: Pervushov et al., 2015) to early Eocene age (Alişan and Gerhard, 1987; Pearson et al., 2006). Questionable records from upper Eocene deposits exist in light of potential core contamination (Frederiksen et al., **2005**) and reworking (Frederiksen et al., **2005**; Slimani et al., 2019). Reports are also well known from strata of middle Paleocene age (Selandian: e.g., Fensome et al., 2008; Ślōdkowska, **2009**; Vasilyeva and Levina, 2010; Ślōdkowska and Gałazka, 2015; Kasiński et al., 2020) to late Paleocene age (Thanetian: Powell et al., **1992**; Cavagnetto and Guerrero, 1999; ?Frieling

et al., **2018**). However, occurrences are most widespread in upper Maastrichtian successions (Georgia: Firth, 1993; Greenland: Nøhr-Hansen, **2012**; North Sea: Schiøler and Wilson, **1993**; Denmark and Sweden: Hultberg, **1985**; Kjellström and Hansen, 1981; Belgium: Slimani, **1994**; Netherlands: Schiøler et al., 1997; Morocco: Rauscher and Doubinger, 1982; Russia: Aleksandrova et al., 2012), although the greatest prevalence of reports have been documented from across K/Pg boundary intervals (New Jersey: Landman et al., 2004a; Vellekoop et al., 2019b; Maryland: Benson, **1976**; Alabama: Moshkovitz and Habib, 1993; Georgia: Firth, 1987; Denmark and Sweden: Hansen, 1977; Morocco: Jbari et al., **2020**) and strata of Danian age (Baja California: Helenes, **1984**; offshore eastern Canada: Barss et al., 1979; Missouri: Frederiksen et al., 1982; Dastas et al., **2014**; Virginia: Edwards et al., **1984**; Edwards, 1989; Maryland: Edwards et al., **1984**; South Carolina: Prowell et al., 1985; Edwards, **1998**; Alabama and Georgia: Edwards, 1980; ?offshore Brasil: Premaor et al., **2018**; France: Cavagnetto and Tambareau, 1998; Sweden: Morgenroth, **1968**; de Coninck, **1975**; Denmark: e.g., Kjellström and Hansen, 1981; Heilmann-Clausen, **1985**; Powell et al., **1992**; Netherlands: Brinkhuis and Schiøler, 1996; Poland: Słodkowska, **2009**; Romania: Țabără et al., 2017; Turkey: Ertuğ et al., 1990; Russia: Vasilyeva, 1990; Amon et al., 2003; Vasilyeva, 2003, **2017**; Vasilyeva and Musatov, 2010a, b; Kazakhstan: Vasilyeva and Levina, 2010; Vasilyeva, 2007, 2013; Senegal: Jan du Chêne, **1987**; Gulf of Guinea: Masure et al., **1998**; ?Angola: Steeman et al., **2020**; Iraq: Naqshabandi, **2018**; New Zealand: Willumsen and Vajda, **2010**).

Remarks. The specimen of *Fibradinium annetorpense* figured from the lower Maastrichtian strata of the Arctic Ocean (Firth and Clark, 1998, pl. 2, figs 10–12) is likely assignable to a different species as the sutural crests and surface texture exceed the relief of that typical of the taxon.

Genus ***Palynodinium*** Gocht, 1970

Palynodinium grallator Gocht, 1970

Occurrence. The range base for *Palynodinium grallator* has been placed in the Santonian on one account (Barss et al., 1979) and in the late Campanian by many others (Foucher and Masure, 1983; Neumann et al., 1983; ?Aurisano, 1989; Costa and Davey, **1992**; Stover et al., 1996; Helenes and Somoza, 1999; Slimani, **2000**, 2001, **2021a**; Bubík et al., 2008; Skupien et al., 2009; Slimani et al., **2011**) with a few reports from strata of early Maastrichtian age (Poland: Jurkowska and Barski, **2017**; Jurkowska et al., 2019). By far the greatest prevalence of records are known from strata dated to latest Maastrichtian–earliest Danian age (Williams et al., 2004). The species has been widely established as an index taxon for the top of the Maastrichtian with the majority of reports hailing from upper Maastrichtian strata in North America (Arkansas: Dastas & Chamberlain Jr. **2021**; Maryland: Benson in Firth, 1987; Landman et al., **2004a**; New Jersey: e.g., Olsson et al., 1997; Landman et al., **2004b**, **2007**; Habib and Saeedi, 2007; Vellekoop et al., 2016, 2019b; Missouri: Oboh-Ikuenobe et al., 2012; Dastas et al., **2014**;

South Carolina: Habib et al., 1994; Georgia: Firth, **1987**; Habib and Miller, 1989; Moshkovitz and Habib, **1993**; Alabama: Moshkovitz and Habib, **1993**; Habib et al., 1996; U.S. Gulf Coast: Larina et al., **2016**; Witts et al., 2018), the North Atlantic (Diederix et al., 1972; Habib and Drugg, **1987**; Norris et al., 2000; Labrador–Baffin Seaway: Fensome et al., **2016**; offshore eastern Canada: Barss et al., 1979; Wade et al., 1995; Fensome et al., 2008, **2009**; Greenland: Nøhr-Hansen and Dam, **1997**; Dam et al., 1998; Pedersen and Nøhr-Hansen, **2014**; offshore West Greenland: Toxwenius, 1986), Europe (Norwegian Sea: Zastrozhnov et al., 2020; North Sea: e.g., Costa and Davey, **1992**; Gradstein et al., 1992; Schröder, 1992; Schiøler and Wilson, **1993**; Köthe, 2012; Gradstein and Waters, 2016; Vieira et al., 2017; Sweden: Kjellström and Hansen, 1981; Hultberg, **1985**, 1986; Hultberg and Malmgren, 1987; Denmark: e.g., Wilson, **1971**; Hansen, **1977**; Hansen et al., 1986; Hansen, 1979b; Brinkhuis et al., 1998; Surlyk et al., **2013**; FitzPatrick et al., **2017**; Netherlands: ?Brinkhuis and Schiøler, **1996**; Schiøler et al., 1997; Brinkhuis et al., 2000; Belgium: Slimani, **2000**; Slimani et al., **2011**; Spain: de Coninck and Smit, **1982**; Brinkhuis et al., 1998; France: Foucher and Masure, 1983; Germany: Gocht, **1970**, 1973; Köthe, **1991**; Egger and Mohamed, **2010**; Austria: Mohamed et al., **2012**, **2013**; Mohamed and Wagreich, **2013**; Poland: Hansen et al., 1989; Machalski et al., **2016**; ?Margielewski et al., 2017; Czech Republic: Gedl, **2004**; Bubik et al., 2002; Romania: Țabără and Slimani, 2017; Țabără et al., **2017**; ?Greece: Mavrides et al., 1994), Asia (Russia: ?Zalinskaya and Naidin, 1985; Sharafutdinova, 1992; Lebedeva et al., **2013**; Kazakhstan: Vasilyeva and Levina, 2007; Iran: Ghourchaei et al., **2015**; India: Misra et al., 1994; Raju et al., 1995; ?Prasad, 1999), Africa (Tunisia: M’Hamdi et al., 2013; Morocco: e.g., Rauscher and Doubinger, **1982**; Guédé et al., **2014**; Slimani et al., **2010**, 2016; Egypt: Berggren et al., 2012; Soliman and Slimani, 2019; Nigeria: Oloto, 1989) and the Southern Hemisphere (offshore Tasmania: Williams et al., **2004**) with numerous instances of persistence into the earliest Danian across K/Pg boundary intervals (New Jersey: Vellekoop et al., 2016, **2019b**; Missouri: Dastas et al., **2014**; Alabama: Moshkovitz and Habib, **1993**; Habib et al., 1996; Denmark: Brinkhuis et al., 1998; FitzPatrick et al., **2017**; Germany: Egger and Mohamed, **2010**; Austria: Mohamed et al., **2012**, **2013**; Czech Republic: Gedl, **2004**; Bubik et al., 2002; Spain: Brinkhuis et al., 1998; Turkey: Açikalin et al., **2015**; Morocco: Slimani et al., **2010**; Jbari et al., **2020**; Egypt: Soliman and Slimani, 2019; Nigeria: Oloto, **1990**; Greenland: Nøhr-Hansen and Dam, 1997; Dam et al., 1998). Exclusively Danian occurrences are known only from immediately above the K/Pg boundary at the Global Boundary Stratotype Section and Point for the base of the Danian Stage near El Kef, Tunisia (Brinkhuis et al., 1998; Vellekoop et al., 2015) and the section at Ouled Haddou, Morocco (Slimani and Toufiq, **2013**). However, M’Hamdi et al. (2013) reported the first occurrence of the species immediately below the K/Pg boundary in the Elles section, Tunisia, contrary to the later findings of Vellekoop et al. (2015). Brinkhuis and Schiøler (**1996**) attributed their observed occurrences in the

Danian Geulhemmerberg section of the Netherlands to reworking as did Landman et al. (2004a, b) with respect to the presence of the species in the Danian strata of New Jersey and Maryland.

Genus *Senegalinium* (Jain and Millepied, 1973) Stover and Evitt, 1978

Senegalinium dilwynense (Cookson and Eisenack, 1965) Stover and Evitt, 1978

Occurrence. Reports of *Senegalinium dilwynense* range from strata of the Late Cretaceous age (late Campanian: Hoek et al., 1996) to early Eocene age (North Sea: de Coninck; 1999; Vieira and Jolley 2020; Belgium: de Coninck, 1980; Bijl et al., 2021) and middle Eocene age (Kurita, 2004; Quattrocchio, 2009; Zaporozhets et al., 2015; Aleksandrova, 2019) with numerous occurrences noted in studies of middle to upper Paleocene successions in both hemispheres (e.g., Selandian: Brinkhuis et al., 2003; Vasilyeva, 2003; Vieira et al., 2020a; Vasilyeva and Musatov, 2010b; Crouch et al., 2014; Steeman et al., 2020; Thanetian: Kurita and Obuse, 1994; Oreshkina and Aleksandrova, 2007; ?Andreeva-Grigorovich et al., 2011; Hollis et al., 2017; Naeher et al., 2019; Vieira et al., 2020b; Vieira and Jolley 2020). Accounts from upper Maastrichtian strata are few (New Zealand: Roncaglia et al., 1999; Israel: Eshet et al., 1994) with greater prevalence of reports known from across K/Pg boundary intervals (New Jersey: Vellekoop et al., 2019b; Chile: Troncoso and Doubinger, 1980; Venezuela: Pocknall et al., 2001; Pocknall and Erlich, 2020 [as *Alterbidinium dilwynense*]; Turkey: Açıkalın et al., 2015; Morocco: Prévôt et al., 1979; Slimani et al., 2010; Australia: Alley and Clarke, 1992; New Zealand: Willumsen, 2011; Raine and Schiøler, 2012; Tasman Plateau: Schellenberg et al., 2004) and strata of Danian age (Virginia: Edwards et al., 1984; Maryland: Edwards et al., 1984; Whitney, 1984; South Carolina: Van Pelt et al., 2000; Lucas-Clark, 2006; Alabama: Moshkovitz and Habib, 1993; Greenland: Nøhr-Hansen, 1994; Australia: Frieling et al., 2018; offshore Tasmania: Partridge, 2008; New Zealand: Willumsen and Vajda, 2010; Strong et al., 1995; Wilson, 1988; Antarctica: e.g., Askin, 1988; Bowman et al., 2012, 2016).

Senegalinium microgranulatum (Stanley, 1965) Stover and Evitt, 1978

Occurrence. Reports of *Senegalinium microgranulatum* range from strata of Late Cretaceous age (Santonian: Prauss, 2015) to early Oligocene age (Sung Zhichen et al., 1978; Mahboub et al., 2019). Numerous Thanetian reports are also known (Gruas-Cavagnetto, 1972, 1976; Köthe, 1991; Peng Shifu, 1992; Lyck and Stemmerik, 2000; Rabbani et al., 2015; Slimani et al., 2016). However, the species has been recognized largely from upper Maastrichtian successions (Wyoming: Stone, 1973; Texas: Zaitzeff and Cross, 1970; Ivory Coast: Guédé et al., 2018) and crossing K/Pg boundary intervals (New Jersey: Vellekoop et al., 2019b; Morocco: Chakir et al., 2020; Jbari et al., 2020) with the greatest prevalence of records from strata of Danian age (Canadian Arctic: Ioannides, 1986; Greenland: Nøhr-Hansen and Dam, 1997; Dam et al., 1998; Manitoba: Kurita and McIntyre, 1995; McIntyre, 1999; North Dakota: Kurita and McIntyre, 1995; South Dakota: Stanley, 1965; South Carolina: Hargrove and Engelhardt, 1997; Lucas-

Clark, **2006**; Georgia: Edwards, **2001**; Brasil: Sarkis et al., 2002; Morocco: Slimani et al., **2010, 2016**; Tunisia: M'Hamdi et al., **2013**; France: Gruas-Cavagnetto et al., 1992; Turkey: Açikalin et al., 2015; China: Xiaoqiao Wan et al., 2014).

Senegalinium obscurum (Drugg, 1967) Stover and Evitt, 1978

Occurrence. Reports of *Senegalinium obscurum* range from strata of Late Cretaceous age (early Campanian: Thompson et al., 1984; Helenes and Téllez-Duarte, 2002) to early Oligocene age (de Coninck, 1986; Mahboub et al., 2019) with only two records hailing from strata of middle Eocene age (Eldholm et al., 1987) and late Eocene age (Andreeva-Grigorovich et al., **2011**). One report exists from lower Maastrichtian strata (Russia: Baraboshkin et al., **2020**), but most reports of Late Cretaceous age are known from upper Maastrichtian strata (Baja California: Helenes and Téllez-Duarte, **2002**; New Jersey: May, **1980**; Maryland: Whitney, 1984; Georgia: Firth, **1993**; Germany: Marheinecke, **1992**; Belgium: Schumacker-Lambry and Chateauneuf, **1976**; Austria: Mohamed et al., 2013; Poland: Machalski et al., **2016**; Colombia: Yepes, 2001) with the highest number of overall occurrences having been documented crossing K/Pg boundary intervals (Manitoba: McIntyre, **1999**; California: Drugg, **1967**; New Jersey: Vellekoop et al., **2019b**; Georgia: Firth, 1987; Alabama: Moshkovitz and Habib, 1993; Greenland: Nøhr-Hansen and Dam, 1997; Dam et al., **1998**; Turkey: Açikalin et al., 2015; Iran: Zarei et al., **2017**; Venezuela: Helenes and Somoza, **1999**; Yepes, 2001; Morocco: Chakir et al., **2020**; Jbari et al., **2020**; Tunisia: M'Hamdi et al., **2013**; Antarctica: Askin, **1988, 1991**; Elliot et al., **1994**), sites possibly in proximity to the K/Pg boundary (Chile: Sanchez et al., 2010) and from strata of Danian age (Manitoba: Kurita and McIntyre, 1995; North Dakota: Kurita and McIntyre, 1995; Baja California: Helenes, **1984**; Missouri: Frederiksen et al., 1982; South Carolina: Hazel et al., 1977; Hargrove and Engelhardt, 1997; Lucas-Clark, **2006**; Alabama: Edwards, 1980; Georgia: Edwards, 1980; Habib and Miller, 1989; Argentina: Guler et al., 2019; Denmark: Lange, **1969**; Belgium: e.g., Schumacker-Lambry and Chateauneuf, 1976; Slimani, 2000, 2001; Morocco: Guédé et al., 2014; Senegal: Jan du Chêne, **1987**; Columbia: Jaramillo et al., 2011; Ukraine: Andreeva-Grygorovych et al., 2017; Russia: Vasilyeva, **2003**; Vasilyeva and Musatov, 2010b; ?Andreeva-Grigorovich et al., **2011**; Shcherbinina et al., 2014; New Zealand: Willumsen and Vajda, 2010; Antarctica: Askin, 1984; Askin and Jacobson, 1996; Bowman et al., **2012, 2016**; Scasso et al., **2020**).

Remarks. *Senegalinium obscurum* and *S. microgranuatrum* conspecificity has been postulated (Ioannides, 1986), although the species have been retained as distinct with the fine to coarsely granulate endophragm of the latter differing from the smooth, translucent endophragm of the former. Both species are noted for their association within the same cyst complex (Kurita and McIntyre, 1995).

Genus *Senoniasphaera* Clarke and Verdier, 1967

Senoniasphaera inornata (Drugg, 1970) Stover and Evitt, 1978

Occurrence. Reports of *Senoniasphaera inornata* range from strata of Late Cretaceous age (Campanian: e.g., Skupien and Mohamed, 2008; Lucas and Ebahili, 2017; ?Bijl et al., **2021**) to Eocene age (Přikryl and Skupien, 2013; Mohamed and Wagreich, **2013**), although Eocene occurrences have been attributed to reworking (Mohamed and Wagreich, **2013**; Fischer et al., 2013). Numerous records from upper Maastrichtian strata are known (Germany: Marheinecke, **1992**; Netherlands: Smit and Brinkhuis, 1996; Russia: Vasilyeva, **2003**; ?Egypt: Soliman and Slimani, **2019**; Iran: Ghourchaei et al., **2015**) along with instances crossing K/Pg boundary intervals (Spain: de Coninck and Smit, 1982; Germany: Köthe, **1991**; India: Garg et al., 2006; Tasman Plateau: Schellenberg et al., 2004). By far the most prevalent reports are those from strata of Danian age in North America (Colorado: Da Gama et al., 2014; Missouri: Oboh-Ikuenobe et al., **2012**; Dastas et al., **2014**; New Jersey: e.g., Landman et al., **2004b**; Habib and Saeedi, 2007; Esmeray-Senlet et al., 2017; Vellekoop et al., **2019b**; Alabama: Drugg, **1970**; Habib et al., 1996; Georgia: e.g., Habib and Miller, 1989; Firth, **1987**; Moshkovitz and Habib, **1993**; Baja California: Helenes, **1984**), South America (Venezuela: Yepes, **2001**), across the Atlantic (Labrador–Baffin Seaway: Fensome et al., **2016**; West Greenland: Nøhr-Hansen and Dam, **1997**; Dam et al., 1998; Pedersen and Nøhr-Hansen, **2014**; East Greenland: Nøhr-Hansen et al., 2011), Europe (Barents Sea: Nagy et al., 2004; North Sea: e.g., Costa et al., 1988; Schiøler and Wilson, 1993; Ebdon et al., 1995; Smith and Møller, 2003; Mudge and Jones, 2004; Köthe, 2007, **2012**; Vieira et al., **2017**, 2020b; Sweden: Hultberg, **1986**; Denmark: e.g., Hansen, **1979a**; Hansen et al., 1986; Surlyk et al., 2013; FitzPatrick et al., 2017; Netherlands: Brinkhuis and Schiøler, 1996; Brinkhuis et al., 2000; Smit and Brinkhuis, 1996; Herngreen et al., **1998**; Vellekoop et al., 2019a; Belgium: Slimani, **2000**, **2001**; Slimani et al., **2011**; Switzerland: Jan du Chêne, **1977**; Germany: Egger and Mohamed, **2010**; Austria: Mohamed and Wagreich, **2013**; Mohamed et al., 2013; Poland: Słodkowska, 2003, 2009; Salamon et al., 2010; Czech Republic: Bubík et al., 2008; Přikryl and Skupien, 2013; Romania: Antonescu and Alexandrescu, **1979**; Țabără and Slimani, **2017**; Țabără et al., **2017**), Asia (Turkey: Açikalin et al., **2015**; Esmeray-Senlet et al., 2015; Russia: e.g., Vasilyeva, 1990; Akhmetiev et al., 2001; Amon et al., 2003; Vasilyeva, **2003**, **2017**; Oreshkina et al., 2008; Akhmetiev et al., 2010; Iakovleva and Aleksandrova, 2013; Kazakhstan: Vasilyeva and Levina, 2010; Andreeva-Grigorovich et al., **2011**; Vasilyeva, 2007, 2013; Iran: Beiranvand et al., 2014; Ghourchaei et al., **2015**; India: Garg et al., 2006; Prasad and Pundir, 2020), Africa (Morocco: e.g., Slimani and Toufiq, **2013**; Guédé et al., **2014**; Slimani et al., **2016**; Jbari et al., **2020**; Tunisia: M’Hamdi et al., **2013**; M’Hamdi et al., 2015; Vellekoop et al., 2015; Egypt: Soliman and Slimani, **2019**; Nigeria: Oloto, **1990**) and throughout the Northern Hemisphere (Williams et al., 2004). Reports from strata of Danian age are also known throughout the Southern Hemisphere (Brasil: Fischer et al., **2013**; Argentina:

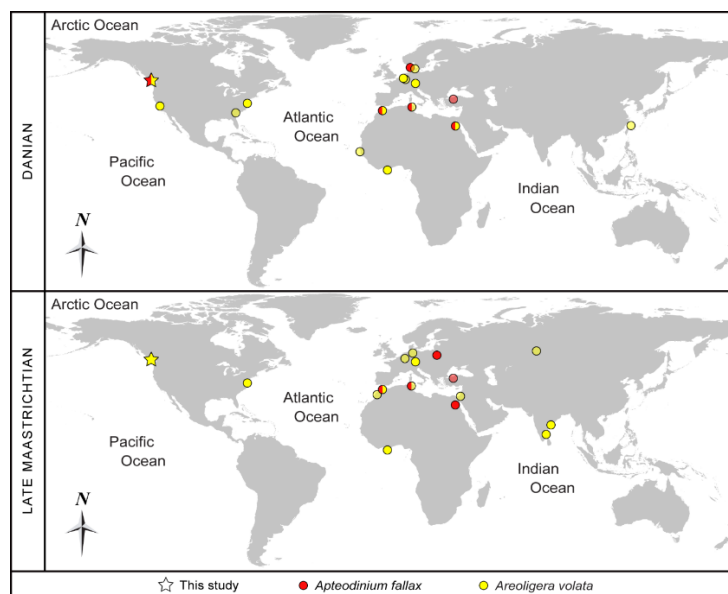
Clyde et al., 2014; Woelders et al., 2017; Guler et al., 2019; González Estebenet et al., 2021; offshore Argentina: Guerstein et al., 2005; Australia: McMinn, 1988; offshore Tasmania: Brinkhuis et al., **2003**; Schellenberg et al., 2004; Williams et al., **2004**; New Zealand: Willumsen, 2011; Raine and Schiøler, **2012**; Willumsen, 2012; Crouch et al., **2014**; Antarctica: Palamarczuk et al., **1984**).

Genus ***Xenikoon*** Cookson and Eisenack, 1960

Xenikoon australis Cookson and Eisenack, 1960

Occurrence. Reports of *Xenikoon australis* range from strata of Late Cretaceous age (late Turonian: Cookson and Eisenack, **1960**; early Campanian: e.g., Helby et al., **1987**; Pirrie et al., **1997**; Morgan et al., 2003; late Campanian: Niechwedowicz, 2019; Slimani et al. **2021b**) to late Paleocene age (Thanetian: e.g., Gibson et al., 1980; ?Edwards et al., **1984**; Edwards, **1989**; Andreeva-Grigorovich et al., **2011**), although many reports are known from upper Maastrichtian successions (Maryland: Benson, **1976**; Landman et al., **2004a, b**; Georgia: Firth, 1987; Denmark: Surlyk et al., **2013**; Belgium: Foucher and Robaszynski, **1977**; Slimani, **2000**, 2001; Netherlands: Schiøler et al., 1997; Germany: Marheinecke, **1992**; Russia: Aleksandrova and Zaporozhets, 2008a; Baraboshkin et al., 2020; Kazakhstan: Vasilyeva and Levina, **2007**; New Zealand: Roncaglia et al., **1999**; Young and Hannah, 2010; Raine and Schiøler, 2012; Antarctica: Dettmann and Thomson, 1987), across K/Pg boundary intervals (New Jersey: Vellekoop et al., **2019b**; Missouri: Dastas et al., **2014**) and strata of Danian age (Maryland and Virginia: Edwards et al., **1984**; Edwards, 1989; Virginia: Gibson et al., 1980; Alabama: Moshkovitz and Habib, 1993; North Sea: Vieira et al., **2017**; Denmark: Heilmann-Clausen, **1985**; Belgium: Foucher and Robaszynski, **1977** New Zealand: Laird et al., 2003).

Remarks. The archaeopyle of *Xenikoon australis* is not always observable in forms herein attributed to the species as is the case in most Oyster Bay Formation specimens. Previously, specimens for which an archaeopyle was not observed have been assigned to *incertae sedis* (Benson, 1976; Heilmann-Clausen, 1985; Andreeva-Grigorovich et al., 2011) and *Xenikoon* sp. A of Foucher and Robaszynski, 1977 (Foucher and Robaszynski, 1977; Surlyk et al., 2013; Vellekoop et al., 2019b) with the possible exception of the specimen figured by Slimani et al. (2021b, fig. 5.3). Aptian-aged specimens recovered from the western North Atlantic are assignable to *Pyxidiella* (Habib, 1972; Hochuli and Kelts, 1977).



Supplementary Fig. 1. Global distribution of the dinoflagellate cysts *Apteodinium fallax* and *Areoligera volata* as reported from strata of late Maastrichtian and Danian age. Colour opacity denotes non-illustrated records. Star indicates location of study area.

References

- Açikalin, S., Vellekoop, J., Ocakoğlu, F., Yilmaz, İ.Ö., Smit, J., Altiner, S.T., Goderis, S., Vonhof, H., Speijer, R.P., Woelders, L., Fornaciari, E., Brinkhuis, H., 2015. Geochemical and palaeontological characterization of a new K-Pg Boundary locality from the northern branch of the Neo-Tethys: Mudurnu—Göynük Basin, NW Turkey. *Cretaceous Research* 52, 251–267.
- Akhmetyev, M.A., Zaporozhets, N.I., Iakovleva, A.I., Aleksandrova, G.N., Beniamovsky, V.N., Oreshkina, T.V., Gnibidenko, Z.N., Dolya, Z.A., 2010. Comparative analysis of marine Paleogene sections and biota from West Siberia and the Arctic region. *Stratigraphy and Geological Correlation* 18, 635–659.
- Akhmetyev, M.A., Aleksandrova, G.N., Amon, E.O., Beniamovsky, V.N., Bugrova, E.M., Vasilyeva, O.N., Glezer, Z.I., Zhelezko, V.I., Zaporozhets, N.I., Kozlova, G.E., Nikolaeva, I.A., Oreshkina, T.V., Panova, L.A., Radionova, E.P., Strelnikova, N.I., Yakovleva, A.I., 2001. Biostratigraphy of the marine Paleogene in the West Siberian Plate. *Stratigraphy and Geological Correlation* 9, 132–158.
- Aleksandrova, G.N., 2019. Palynological characteristic of the Eocene–early Miocene of the Kvachina Bay section, West Kamchatka. *Stratigraphy and Geological Correlation* 27, 361–387.
- Aleksandrova, G.N., Zaporozhets, N.I., 2008a. Palynological characteristics of Upper Cretaceous and Paleogene deposits on the west of the Sambian Peninsula (Kaliningrad region), Part 1. *Stratigraphy and Geological Correlation* 16, 295–316.
- Aleksandrova, G.N., Zaporozhets, N.I., 2008b. Palynological characteristics of Upper Cretaceous and Paleogene deposits on the west of the Sambian Peninsula (Kaliningrad region), Part 2. *Stratigraphy and Geological Correlation* 16, 528–539.
- Aleksandrova, G.N., Oreshkina, T.V., Iakovleva, A.I., Radionova, E.P., 2012. Late Paleocene–early

- Eocene diatoms and dinocysts from biosiliceous facies of the Middle Trans-Urals region. *Stratigraphy and Geological Correlation* 20, 380–404.
- Aleksandrova, G.N., Beniamovsky, V.N., Zaporozhets, N.I., Zastrozhnov, A.S., Zastrozhnov, S.I., Tabachnikova, I.P., Oreshkina, T.V., Zakrevskaya, E.Y., 2011. Paleogene of the southwestern Volgograd region (Borehole 13, Gremyach'e Area). 1. Biostratigraphy. *Stratigraphy and Geological Correlation* 19, 310–336.
- Alişan, C., Gerhard, J.E., 1987. Palynostratigraphy and source rock properties of three wells drilled in the North Thrace Basin. *Proceedings of the 7th Petroleum Congress of Turkey*, 461–474.
- Alley, N.F., Clarke, J.D.A., 1992. Stratigraphy and palynology of Mesozoic sediments from the Great Australian Bight area, southern Australia. *Bureau of Mineral Resources, Journal of Australian Geology and Geophysics* 13, 113–129.
- Amano, K., Kurita, H., 2020. A new Paleocene species of *Myonera* (Bivalvia: Cuspidariidae) from eastern Hokkaido, northern Japan. *The Nautilus* 134, 51–56.
- Amenábar, C.R., Caramés, A., Lescano, M., Concheyro, A., 2014. Palinología y micropaleontología del Cretácico de la Cuenca James Ross, Antártida. Estado actual del conocimiento. *Boletín Geológico y Minero* 125, 493–559 (in Spanish).
- Amon, E.O., Vasilyeva, O.N., Zhelezko, V.I., 2003. Stratigraphy of the Talitsa Horizon (Paleocene) in the Central Trans-Urals. *Stratigraphy and Geological Correlation* 11, 278–292.
- Andreeva-Grigorovich, A.S., Suprun, I.S., 2016. Haptophyceae and dinophyceae fossil algae from the Paleogene sediments of the Ukrainian Carpathian region. *Algae in the evolution of the biosphere: Proceedings of the 2nd Paleoalgal Conference (Novosibirsk, October 10–16)*, 3–6 (in Russian).
- Andreeva-Grigorovich, A.S., Zaporozhetz, N.I., Shevchenko, T.V., Aleksandrova, G.N., Vasilyeva, O.N., Iakovleva, A.I., Stotland, A.B., Savitskaya, N.A., 2011. Atlas of Paleogene dinocysts of Ukraine, Russia and adjacent countries. *Naukoma Dumka, Kiev*, 244 pp., 64 pls. (in Russian).
- Andreeva-Grygorovich, A.S., Maslun, N.V., Ivanik, M.M., Waga, D.D., Zhabina, N.M., Hnylko, S.R., Suprun, I.S., Minutsova, L.G., 2017. An integrated planktonic (foraminifera, calcareous nannofossils, dinocysts) biostratigraphy of the Paleogene sediments from the oil and gas bearing provinces of Ukraine. *Collection of Scientific Works of the Institute of Geological Sciences, National Academy of Sciences of Ukraine* 10, 95–114.
- Antonescu, E., Alexandrescu, G., 1979. Données préliminaires sur les dinoflagellés des couches de Hangu (Sénonian–Paléocène). *Dări de Seamă ale şiedinţelor, Institutul de Geologie şi Geofizică*. 3. *Paleontologie* 66, 61–93 (in French).
- Askin, R.A., 1984. Palynological investigations of the James Ross Island basin and Robertson Island, Antarctic Peninsula. *Antarctic Journal of the United States* 19, 6–7.
- Askin, R.A., 1988. Campanian to Paleocene palynological succession of Seymour and adjacent islands, northeastern Antarctic Peninsula. *Geological Society of America, Memoir* 169, 131–153.
- Askin, R.A., 1991. Preliminary palynology and stratigraphic interpretations from a new Cretaceous–Tertiary boundary section from Seymour Island. *Antarctic Journal of the United States* 25, 42–44.
- Askin, R.A., Jacobson, S.R., 1996. Palynological change across the Cretaceous–Tertiary boundary on Seymour Island, Antarctica: environmental and depositional factors. In: Macleod, N., Keller, G. (Eds.), *Cretaceous–Tertiary mass extinctions: biotic and environmental changes*. W.W. Norton & Co., New York, pp. 7–25.
- Aurisano, R., 1989. Upper Cretaceous dinoflagellate biostratigraphy of the subsurface Atlantic coastal plain of New Jersey and Delaware, U.S.A. *Palynology* 13, 143–179.
- Awad, W.K., Oboh-Ikuenobe, F.E., 2016. Early Paleogene dinoflagellate cysts from ODP Hole 959D, Côte d'Ivoire-Ghana Transform Margin, West Africa: New species, biostratigraphy and paleoenvironmental implications. *Journal of African Earth Sciences* 123, 123–144.
- Baraboshkin, E.Y., Guzhikov, A.Y., Aleksandrova, G.N., Fomin, V.A., Pokrovsky, B.G., Grishchenko, V.A., Manikin, A.G., Naumov, E.V., 2020. New sedimentological, magnetostratigraphic, and biostratigraphic data on the Campanian–Maastrichtian of Beshkosh Mountain, southwest Crimea.

- Stratigraphy and Geological Correlation 28, 816–858.
- Barreda, V.D., Cúneo, N.R., Wilf, P., Currano, E.D., Scasso, R.A., Brinkhuis, H., 2012. Cretaceous/Paleogene floral turnover in Patagonia: drop in diversity, low extinction, and a *Classopollis* spike. *PLoS One* 7, e52455.
- Barron, J., Larsen, B., Baldauf, J., Alibert, C., Berkowitz, S., Caulet, J.-P., Chambers, S., Cooper, A., Cranston, R., Dorn, W., Ehrmann, W., Fox, R., Fryxell, G., Hambrey, M., Huber, B., Jenkins, C., Kang, S.-H., Keating, B., Mehl, K., Noh, I., Oilier, G., Pittenger, A., Sakai, H., Schroder, C., Solheim, A., Stockwell, D., Thierstein, H., Tocher, B., Turner, B., Wuchang Wei, 1989. Site 738. In: Hare, C., Mazzullo, E.K. (Eds.), *Proceedings of the Ocean Drilling Program, Initial Reports* 119, College Station, Texas, pp. 229–288.
- Barss, M.S., Bujak, J.P., Williams, G.L., 1979. A palynological zonation and correlation of sixty-seven wells. Geological Survey of Canada, Paper 78-24, 1–118.
- Beiranvand, B., Zaghib-Turki, D., Ghasemi-Nejad, E., 2014. Integrated biostratigraphy based on planktonic foraminifera and dinoflagellates across the Cretaceous/Paleogene (K/Pg) transition at the Izeh section (SW Iran). *Comptes Rendus Palevol* 13, 235–258.
- Bell, D.G., Bjorøy, M., Grogan, P., Kilenyi, T., Trayner, P., 1990. Better prospect evaluation with organic geochemistry, biostratigraphy and seismics. *Oilfield Review* 2, 24–42.
- Bellion, Y., Ausseil, J., Colin, J.-P., Jan du Chêne, R., Khatib, R., De Klasz, I., De Klasz, S., Perch-Nielsen, K., Saint-Marc, P., Sarr, R., 1985. Age paléocène de la Formation des Madeleines de la région de Dakar (Sénégal). *Comptes Rendus l'Académie des Sciences, Série IIA* 301, 937–940 (in French).
- Benson, D.G., 1976. Dinoflagellate taxonomy and biostratigraphy at the Cretaceous-Tertiary boundary, Round Bay, Maryland. *Tulane Studies in Geology and Paleontology* 12, 169–233.
- Berggren, W.A., Alegret, L., Aubry, M.-P., Cramer, B.S., Dupuis, C., Goolaerts, S., Kent, D. V., King, C., Knox, R.W.O'B., Obaidalla, N., Ortiz, S., Ouda, K.A.K., Abdel-Sabour, A., Salem, R., Senosy, M.M., Soliman, M.F., Soliman, A., 2012. The Dababiya corehole, Upper Nile Valley, Egypt: Preliminary results. *Austrian Journal of Earth Sciences* 105, 161–168.
- Bijl, P., Guerin, G., Sanmiguel, J.E., Sluijs, A., Casadio, S., Valencia, V., Amenábar, C., Encinas, A., 2021. Campanian–Eocene dinoflagellate cyst biostratigraphy in the southern Andean foreland basin: Implications for Drake Passage throughflow. *Andean Geology* 48, 185–218.
- Bowman, V.C., Francis, J.E., Riding, J.B., Hunter, S.J., Haywood, A.M., 2012. A latest Cretaceous to earliest Paleogene dinoflagellate cyst zonation from Antarctica, and implications for phytoprovincialism in the high southern latitudes. *Review of Palaeobotany and Palynology* 171, 40–56.
- Bowman, V., Ineson, J., Riding, J., Crame, J., Francis, J., Condon, D., Whittle, R., Ferraccioli, F., 2016. The Paleocene of Antarctica: Dinoflagellate cyst biostratigraphy, chronostratigraphy and implications for the palaeo-Pacific margin of Gondwana. *Gondwana Research* 38, 132–148.
- Brinkhuis, H., Leereveld, H., 1988. Dinoflagellate cysts from the Cretaceous/Tertiary boundary sequence of El Kef, northwest Tunisia. *Review of Palaeobotany and Palynology* 56, 5–19.
- Brinkhuis, H., Schiøler, P., 1996. Palynology of the Geulhemmerberg Cretaceous/Tertiary boundary section (Limburg, SE Netherlands). *Geologie En Mijnbouw* 75, 193–213.
- Brinkhuis, H., Zachariasse, W.-J., 1988. Dinoflagellate cysts, sea level changes and planktonic foraminifers across the Cretaceous–Tertiary boundary at El Haria, northwest Tunisia. *Marine Micropaleontology* 13, 153–191.
- Brinkhuis, H., Klinkenberg, E., Williams, G.L., Fensome, R.A., 2000. Two unusual new dinoflagellate cyst genera from the Bunde Borehole, Maastrichtian type area, southern Netherlands. *Review of Palaeobotany and Palynology* 110, 93–110.
- Brinkhuis, H., Bujak, J.P., Smit, J., Versteegh, G.J.M., Visscher, H., 1998. Dinoflagellate-based sea surface temperature reconstructions across the Cretaceous–Tertiary boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology* 141, 67–83.
- Brinkhuis, H., Sengers, S., Sluijs, A., Warnaar, J., Williams, G.L., 2003. Latest Cretaceous–earliest

- Oligocene and Quaternary dinoflagellate cysts, ODP Site 1172, East Tasman Plateau. In: Exon, N.F., Kennet, J.P., Malone, J.M. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results 189*, College Station, Texas, pp. 1–48.
- Bubík, M., Skupien, P., Švábenická, L., 2008. Stratigraphy of the Cretaceous oceanic red beds of the Carpathian Flysch in Moravia. *Geologické výzkumy na Moravě a ve Slezsku* 15, 46–52 (in Czech).
- Bubík, M., Adamová, M., Bák, M., Franců, J., Gedl, P., Mikuláš, R., Švábenická, L., Uchman, A., 2002. Results of the investigations at the Cretaceous/Tertiary boundary in the Magura Flysch near Uzgrůň. *Geologické výzkumy na Moravě a ve Slezsku* 10, 18–22 (in Czech).
- Bütschli, O., 1885. Erster Band. Protozoa. In: Bronns, H.G. (Ed.), *Die Klassen Und Ordnungen Des Thier-Reichs, Wissenschaftlich Dargestellt in Wort Und Bild*. C. F. Winter'sche Verlagsbuchhandlung, Leipzig and Heidelberg, pp. 865–1088 (in German).
- Cavagnetto, C., Guerrero, N., 1999. Pollens et dinoflagellés du Paléogène inférieur turbiditique du Béarn. Comparison with the platform assemblages of the Pyrenean foothills. *Géologie de la France* 3, 17–35 (in French).
- Cavagnetto, C., Tambareau, Y., 1998. Palynologie du Selandien d'Oraas (Pyrénées-Atlantiques, France): comparaison avec le microplancton du Danien-Selandien connu dans le monde. *Geodiversitas* 20, 239–261 (in French).
- Chakir, S., Slimani, H., Hssaida, T., Kocsis, L., Gheerbrant, E., Bardet, N., Jalil, N.-E., Mouflih, M., Mahboub, I., Jbari, H., 2020. Dinoflagellate cyst evidence for the age, palaeoenvironment and paleoclimate of a new Cretaceous–Paleogene (K/Pg) boundary section at the Bou Angueur syncline, Middle Atlas, Morocco. *Cretaceous Research* 106, 104219.
- Clarke, R.F.A., Verdier, J.-P., 1967. An investigation of microplankton assemblages from the Chalk of the Isle of Wight, England. *Verhandelingen der Koninklijke Nederlandse Akademie van Wetenschappen, Afdeling Natuurkunde, Eerste Reeks* 24, 1–96, pls. 1–17.
- Clyde, W.C., Wilf, P., Iglesias, A., Slingerland, R.L., Barnum, T., Bijl, P.K., Bralower, T.J., Brinkhuis, H., Comer, E.E., Huber, B.T., Ibañez-mejia, M., Jicha, B.R., Krause, J.M., Schueth, J.D., Singer, B.S., Raigemborn, M.S., Schmitz, M.D., Sluijs, A., Del Carmen Zamaloa, M., 2014. New age constraints for the Salamanca Formation and lower Río Chico Group in the western San Jorge Basin, Patagonia, Argentina: Implications for Cretaceous–Paleogene extinction recovery and land mammal age correlations. *Geological Society of America Bulletin* 126, 289–306.
- Cookson, I.C., Eisenack, A., 1960. Microplankton from Australian Cretaceous sediments. *Micropaleontology* 6, 1–18.
- Cookson, I.C., Eisenack, A., 1965b. Microplankton from the Paleocene Pebble Point Formation, southwestern Victoria. *Proceedings of the Royal Society of Victoria* 79, 139–146, pl. 18–19.
- Costa, L.I., Davey, R.J., 1992. Dinoflagellate cysts of the Cretaceous System. In: Powell, A.J. (Ed.), *A stratigraphic index of dinoflagellate cysts*. British Micropalaeontological Society Publications Series, Chapman & Hall, London, pp. 99–131, pls. 3.1–3.11.
- Costa, L.I., Manum, S.B., Meyer, K.-J., 1988. Great Britain/Norway; The Viking Graben. *Geologisches Jahrbuch, Reihe A* 100, 330–332.
- Crame, J.A., Pirrie, D., Riding, J.B., Thomson, M.R.A., 1991. Campanian–Maastrichtian, (Cretaceous) stratigraphy of the James Ross Island area, Antarctica. *Journal of the Geological Society, London* 148, 1125–1140.
- Crouch, E.M., Willumsen, P.S., Kulhanek, D.K., Gibbs, S.J., 2014. A revised Paleocene (Teurian) dinoflagellate cyst zonation from eastern New Zealand. *Review of Palaeobotany and Palynology* 202, 47–79.
- Da Gama, R.O.B.P., Lutz, B., Desjardins, P., Thompson, M., Prince, I., Espejo, I., 2014. Integrated paleoenvironmental analysis of the Niobrara Formation: Cretaceous Western Interior Seaway, northern Colorado. *Palaeogeography, Palaeoclimatology, Palaeoecology* 413, 66–80.
- Dam, G., Nøhr-Hansen, H., Kennedy, W.J., 1998. The northernmost marine Cretaceous–Tertiary boundary section: Nuussuaq, West Greenland. *Geology of Greenland Survey Bulletin* 180, 138–144.
- Damassa, S.P., 1979a. Eocene dinoflagellates from the Coastal Belt of the Franciscan Complex, northern

- California. *Journal of Paleontology* 53, 815–840, pls. 1–8.
- Damassa, S.P., 1979b. Danian dinoflagellates from the Franciscan Complex, Mendocino County, California. *Palynology* 3, 191–207.
- Damassa, S.P., 1984. Morphologic variability and paraplate configuration of the dinoflagellate genus *Danea* Morgenroth 1968. *Palynology* 8, 51–69.
- Damassa, S.P., 1988. *Carpatella cornuta* Grigorovich 1969 (Dinophyceae)—a member of the *Aptiana-Ventriosum* complex. *Palynology* 12, 167–177.
- Dastas, N.R., Chamberlain Jr, J.A., Garb, M.P., 2014. Cretaceous–Paleogene dinoflagellate biostratigraphy and the age of the Clayton Formation, southeastern Missouri, USA. *Geosciences* 4, 1–29.
- Dastas, N.R., Chamberlain Jr., J.A., 2021. *Cyclonephelium brevireticulatum*, a new dinoflagellate cyst from the Arkadelphia Formation (upper Maastrichtian), Hot Spring County, Arkansas, USA. *Palynology*.
- de Coninck, J., 1968. Dinophyceae et Acritarcha de l'Yprésien du sondage de Kallo. *Mémoires de l'Institut Royal des Sciences Naturelles de Belgique* 161, 1–67, pls. 1–17 (in French).
- de Coninck, J., 1975. Organic-walled microfossils from the upper Danian and middle Paleocene of southern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 97, 326–337.
- de Coninck, J., 1980. Organic walled microfossils in the clay of leper in the Overijse borehole. *Bulletin de la Société belge de Géologie* 98, 201–215.
- de Coninck, J., 1986. Organic walled phytoplankton from the Bartonian and Eo-Oligocene transitional deposits of the Woensdrecht Borehole, southern Netherlands. *Mededelingen Rijks Geologische Dienst, Nieuwe Serie* 40, 1–49.
- de Coninck, J., 1999. Phytoplankton à paroi organique et phases transgressives vers la transition Paléocène–Éocène dans la partie méridionale du Bassin de la Mer du Nord. *Bulletin de la Société belge de Géologie* 105, 139–169 (in French).
- de Coninck, J., Smit, J., 1982. Marine organic-walled micro-fossils at the Cretaceous-Tertiary boundary in the Barranco Del-Gredero (S.E. Spain). *Geologie en Mijnbouw* 61, 173–178.
- de Oliveira Alves, M.A., Santos, P.R.S., de Lima Filho, M., 2019. Biostratigraphia do limite Cretáceo-Paleógeno da bacia da Paraíba com base na Palinologia. *Estudos Geológicos* 29, 3–24 (in Portuguese).
- Deflandre, G., Cookson, I. C. 1955. Fossil microplankton from Australian late Mesozoic and Tertiary sediments. *Australian Journal of Marine and Freshwater Research* 6, 242–313, pls. 1–9.
- Dettmann, M.E., Thomson, M.R.A., 1987. Cretaceous palynomorphs from the James Ross Island area, Antarctica—a pilot study. *British Antarctic Survey Bulletin* 77, 13–59.
- Diederix, D.O.J., De Haan, R., Tichler, W.O., 1972. Organic microfossils. In: Pimm, A.C. (Ed.), Site 138. Deep Sea Drilling Project, Initial Reports 14, U.S. Government Printing Office, Washington, pp. 135–155.
- Drugg, W.S., 1967. Palynology of the upper Moreno Formation (Late Cretaceous-Paleocene) Escarpado Canyon, California. *Palaeontographica, Abteilung B* 120, 1–71, pls. 1–9.
- Drugg, W.S., 1970. Some new genera, species, and combinations of phytoplankton from the lower Tertiary of the Gulf Coast, U.S.A. *Proceedings of the North American Paleontological Convention, Chicago, September 1969, Part G*, 809–843.
- Durugbo, E.U., 2016. Palynostratigraphy, palynofacies and thermal maturation of the Nsukka Formation from an excavation site in Okigwe, southeastern Nigeria. *Palaeontologica Africana* 50, 76–92.
- Ebdon, C.C., Granger, P.J., Johnson, H.D., Evans, A.M., 1995. Early Tertiary evolution and sequence stratigraphy of the Faeroe-Shetland Basin: implications for hydrocarbon prospectivity. *Geological Society, London, Special Publications* 90, 51–69.
- Edwards, L.E., 1980. Dinoflagellate biostratigraphy: A first look. In: Reinhardt, J., Gibson, T.G. (Eds.), *Upper Cretaceous and lower Tertiary geology of the Chattahoochee River Valley, western Georgia and eastern Alabama*. In: Frey, R.W. (Ed.), *Excursions in southeastern Geology: Geological Society of America, annual meeting (Atlanta, Georgia), field trip guidebooks* 2, pp. 424–427.

- Edwards, L.E., 1989. Supplemented graphic correlation: a powerful tool for paleontologists and nonpaleontologists. *Palaios* 4, 127–143.
- Edwards, L.E., 1998. Dinoflagellates from the Black Mingo Group (Paleocene) of South Carolina. *Transactions of the American Philosophical Society, New Series* 88, 28–48.
- Edwards, L.E., 2001. Dinocyst biostratigraphy of Tertiary sediments from five cores from Screven and Burke Counties, Georgia. United States Geological Survey, Professional Paper 1603–G, G1–G25.
- Edwards, L.E., Goodman, D.K., Witmer, R.J., 1984. Lower Tertiary, (Pamunkey Group), dinoflagellate biostratigraphy, Potomac River area, Virginia and Maryland. In: Frederiksen, N.O., Krafft, K. (Eds.), *Cretaceous and Tertiary stratigraphy, paleontology and structure, southwestern Maryland and northeastern Virginia*, American Association of Stratigraphic Palynologists, field trip volume and guidebook, pp. 137–152.
- Edwards, L.E., Gohn, G.S., Bybell, L.M., Chirico, P.G., Christopher, R.A., Frederiksen, N.O., Prowell, D.C., Self-Trail, J.M., Weems, R.E., 2000. Supplement to the preliminary stratigraphic database for subsurface sediments of Dorchester County, South Carolina. United States Geological Survey, Open-File Report 00-049B, 1 CD-ROM.
- Egger, H., Mohamed, O., 2010. A slope-basin model for early Paleogene deep-water sedimentation (Achthal Formation nov. nom.) at the Tethyan continental margin (Ultrahelvetic realm) of the European Plate (Eastern Alps, Germany). *Australian Journal of Earth Sciences* 103, 121–137.
- Eisenack, A., 1938. Die phosphoritknollen der Bernsteinformation als überlieferer Tertiären planktons. *Schriften der Physikalisch-Ökonomischen Gesellschaft zu Königsberg* 70, 181–188 (in German).
- Eisenack, A., 1958. Mikroplankton aus dem norddeutschen Apt, nebst einigen bemerkungen über fossile Dinoflagellaten. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 106, 383–422, pls. 21–27 (in German).
- Eldholm, O., Thiede, J., Taylor, E., Barton, C.A., Bjørklund, K., Bleil, U., Ciesielski, P.R., Desprairies, A., Donnally, D., Froget, C., Goll, R., Henrich, R., Jansen, E., Krissek, L., Kvenvolden, K.A., LeHuray, A.P., Love, D., Lysne, P., McDonald, T., Mudie, P.J., Osterman, L., Parson, L.M., Phillips, J., Pittenger, A., Gunnbjørg, Q., Schönharting, G., Viereck, L., 1987. Site 643: Norwegian Sea. In: Winkler, W.R. (Ed.), *Proceedings of the Ocean Drilling Program, Initial Reports*, 104, College Station, Texas, pp. 455–615.
- Elliot, D.H., Askin, R.A., Kyte, F.T., Zinsmeister, W.J., 1994. Iridium and dinocysts at the Cretaceous-Tertiary boundary on Seymour Island, Antarctica: Implications for the K-T event. *Geology* 22, 675–678.
- Elsik, W.C., Crabaugh, J.P., 2001. Palynostratigraphy of the upper Paleocene and lower Eocene Wilcox Group in the northwestern Gulf of Mexico Basin. In: Goodman, D.K., Clarke, R.T. (Eds.), *Proceedings of the 9th International Palynological Congress*, Houston, Texas, U.S.A., 1996. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 233–237.
- Erkmen, U., Sadek, A., 1981. Contribution to the stratigraphy of the Germav Formation, (Late Cretaceous–early Tertiary), in SE Turkey by means of dinoflagellates and nannoplankton. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte* 3, 129–140.
- Ertuğ, K., Bozdoğan, N., Ediger, V.Ş., 1990. Dinoflagellate cysts from the Maastrichtian-Paleocene boundary, S. E. Anatolia, Turkey. *Revista Espanola de Micropaleontologia* 22, 183–198.
- Eshet, Y., Hoek, R., Almogi-Labin, A., 1994. A new dinocyst-based biostratigraphic framework for Campanian–Maastrichtian organic rich-carbonate sequences in Israel. *Geological Survey of Israel, Report* 94, 1–24.
- Esmeray-Senlet, S., Özkan-Altin, S., Altin, D., Miller, K.G., 2015. Planktonic foraminiferal biostratigraphy, microfacies analysis, sequence stratigraphy, and sea-level changes across the Cretaceous-Paleogene boundary in the Haymana Basin, Central Anatolia, Turkey. *Journal of Sedimentary Research* 85, 489–508.
- Esmeray-Senlet, S., Miller, K.G., Sherrell, R.M., Senlet, T., Vellekoop, J., Brinkhuis, H., 2017. Iridium profiles and delivery across the Cretaceous/Paleogene boundary. *Earth and Planetary Science Letters* 457, 117–126.

- Evitt, W.R., 1973. Maestrichtian *Aquilapollenites* in Texas, Maryland, and New Jersey. *Geoscience and Man* 7, 31–38, 2 pls.
- Exon, N.F., Kennett, J.P., Malone, M.J., Brinkhuis, H., Chaproniere, G.C.H., Ennyu, A., Fothergill, P., Fuller, M.D., Grauert, M., Hill, P.J., Janecek, T.R., Kelly, D.C., Latimer, J.C., Nees, S., Ninnemann, U.S., Nürnberg, D., Pekar, S.F., Pellaton, C.C., Pfuhl, H.A., Robert, C.M., McGonigal Roessig, K.L., Röhl, U., Schellenberg, S.A., Shevenell, A.E., Stickley, C.E., Suzuki, N., Touchard, Y., Wuchang Wei, White, T.S., 2001. Site 1172. In: Exon, N.F., Kennett, J.P., Malone, M.J. (Eds.), *Proceedings of the Ocean Drilling Program, Initial Reports 189*, College Station, Texas, pp. 1–149.
- Fensome, R.A., Nøhr-Hansen, H., Williams, G.L., 2016. Cretaceous and Cenozoic dinoflagellate cysts and other palynomorphs from the western and eastern margins of the Labrador–Baffin Seaway. *Geological Survey of Denmark and Greenland Bulletin* 36, 1–143.
- Fensome, R.A., Williams, G.L., MacRae, R.A., 2009. Late Cretaceous and Cenozoic fossil dinoflagellates and other palynomorphs from the Scotian Margin, offshore eastern Canada. *Journal of Systematic Palaeontology* 7, 1–79.
- Fensome, R.A., Williams, G.L., MacRae, R.A., 2019. The Lentin and Williams index of fossil dinoflagellates 2019 edition. *American Association of Stratigraphic Palynologists Contributions Series* 50, 1173 pp.
- Fensome, R.A., Taylor, F.J.R., Norris, G., Sarjeant, W.A.S., Wharton, D.I., Williams, G.L., 1993. A classification of fossil and living dinoflagellates. *Micropaleontology, Special Publication* 7, 1–351.
- Fensome, R.A., Crux, J.A., Gard, I.G., Macrae, R.A., Williams, G.L., Thomas, F.C., Fiorini, F., Wach, G., 2008. The last 100 million years on the Scotian Margin, offshore eastern Canada: an event-stratigraphic scheme emphasizing biostratigraphic data. *Atlantic Geology* 44, 93–126.
- Ferrow, E., Vajda, V., Koch, C.B., Peucker-Ehrenbrink, B., Willumsen, P.S., 2011. Multiproxy analysis of a new terrestrial and a marine Cretaceous–Paleogene (K–Pg) boundary site from New Zealand. *Geochimica et Cosmochimica Acta* 75, 657–672.
- Firth, J.V., 1987. Dinoflagellate biostratigraphy of the Maastrichtian to Danian interval in the U.S. Geological Survey Albany Core, Georgia, U.S.A. *Palynology* 11, 199–216.
- Firth, J.V., 1993. Dinoflagellate assemblages and sea-level fluctuations in the Maastrichtian of southwest Georgia. *Review of Palaeobotany and Palynology* 79, 179–204.
- Firth, J.V., Clark, D.L., 1998. An early Maastrichtian organic-walled phytoplankton cyst assemblage from an organic-rich black mud in Core FI-533, Alpha Ridge: evidence for upwelling conditions in the Cretaceous Arctic Ocean. *Marine Micropaleontology* 34, 1–27.
- Fischer, T.V., Souza, P.A., Escamilla, J.H., Arai, M., 2013. Associações palinológicas do Paleógeno da Bacia De Pelotas (Poço BP-1, Brasil) e seu significado estratigráfico. *Geociência* 32, 677–695 (in Portuguese).
- FitzPatrick, M.E.J., Forber, D.A., Hart, M.B., 2017. Dinocyst stratigraphy and palaeoenvironmental interpretation of the Cretaceous/Paleogene boundary at Stevns Klint, Denmark. *Cretaceous Research* 87, 408–421.
- Foucher, J.-C., Masure, E., 1983. Dinoflagelles (Kystes). *Géologie Méditerranéenne* 10, 419–420 (in French).
- Foucher, J.-C., Robaszynski, F., 1977. Microplancton des silex du bassin de mons (Belgique) (dinoflagellés Crétacés et Daniens). *Annales de Paleontologie (Invertébrés)* 63, 19–58 (in French).
- Fourcade, E., Alonzo, M., Barrillas, M., Bellier, J.-P., Bonneau, M., Cosillo, A., Cros, P., Debrabant, P., Gardin, S., Masure, E., Philip, J., Renard, M., Rocchia, R., Romero, J., 1997. La limite Crétacé/Tertiaire dans le sud-ouest du Petén (Guatemala). *Comptes Rendus de l'Académie des Sciences, Series IIA: Earth and Planetary Science* 325, 57–64 (in French).
- Frederiksen, N.O., Edwards, L.E., Self-Trail, J.M., Bybell, L.M., Cronin, T.M., 2005. Paleontology of the impact-modified and impact-generated sediments in the USGS-NASA Langley Core, Hampton, Virginia. *United States Geological Survey, Professional Paper* 1688, D1–D37, pls. D1–D5.
- Frederiksen, N.O., Bybell, L.M., Christopher, R.A., Crone, A.J., Edwards, L.E., Gibson, T.G., Hazel, J.E., Repetski, J.E., Russ, D.P., Smith, C.C., Ward, L.W., 1982. Biostratigraphy and paleoecology of

- lower Paleozoic, Upper Cretaceous and lower Tertiary rocks in U.S. Geological Survey New Madrid test wells, southeastern Missouri. *Tulane Studies in Geology and Paleontology* 17, 23–45.
- Frieling, J., Sluijs, A., 2018. Towards quantitative environmental reconstructions from ancient non-analogue microfossil assemblages: Ecological preferences of Paleocene–Eocene dinoflagellates. *Earth-Science Reviews* 185, 956–973.
- Garg, R., Khawaja-Ateequzaman, Prasad, V., 2006. Significant dinoflagellate cyst biohorizons in the Upper Cretaceous–Palaeocene succession of the Khasi Hills, Meghalaya. *Journal of the Geological Society of India* 67, 737–747.
- Gedl, P., 2004. Dinoflagellate cyst record of the deep-sea Cretaceous–Tertiary boundary at Uzgruň, Carpathian Mountains, Czech Republic. *Geological Society, London, Special Publications* 230, 257–273.
- Ghourchaei, S., Ghasemi-Nejad, E., Vahidinia, M., Ashouri, A., 2015. Paleoenvironmental reconstruction of the Upper Cretaceous succession (Abtalkh Formation) of the Kopeh-Dagh Basin, northeastern Iran based on foraminiferal and palynological analyses. *Arabian Journal of Geosciences* 8, 2153–2168.
- Gibson, T.G., Andrews, G.W., Bybell, L.M., Frederiksen, N.O., Hansen, T., Hazel, J.E., McLean, D.M., Witmer, R.J., Van Nieuwenhuise, D.S., 1980. Biostratigraphy of the Tertiary strata of the core. Virginia Division of Mineral Resources Publication 20, 14–30.
- González Estebenet, M.S., Guler, M.V., Pérez Panera, J. P., 2021. Late Maastrichtian to Danian organic-walled dinoflagellate cysts and calcareous nannofossils from eastern Austral Basin, Patagonia, Argentina. *Review of Palaeobotany and Palynology* 285, 104342.
- Gocht, H., 1970. Dinoflagellaten-Zysten aus einem Geschiebefeuerstein und ihr Erhaltungszustand. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte* 3, 129–140 (in German).
- Gocht, H., 1973. Zur validität der gattung *Palynodinium* Gocht. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte* 8, 455–457 (in German).
- Gradstein, F.M., Waters, C.N., 2016. Stratigraphic guide to the Cromer Knoll, Shetland and Chalk Groups, North Sea and Norwegian Sea. *Newsletters on Stratigraphy* 49, 71–280.
- Gradstein, F.M., Kristiansen, I.L., Loemo, L., Kaminski, M.A., 1992. Cenozoic foraminiferal and dinoflagellate cyst biostratigraphy of the central North Sea. *Micropaleontology* 38, 101–137.
- Gruas-Cavagnetto, C., 1972. Étude palynoplantologique de deux gisements du Thanétien des environs de Reims. *Revue de Micropaléontologie* 15, 63–74 (in French).
- Gruas-Cavagnetto, C., 1976. Les marqueurs stratigraphiques (dinoflagellés) de l'Éocène du Bassin de Paris et de la Manche Orientale. *Revue de Micropaléontologie* 18, 221–228 (in French).
- Gruas-Cavagnetto, C., Tambareau, Y., Villatte, J., 1992. Découverte de pollens, dinoflagellés et foraminifères dans le Danien des Petites Pyrénées: implications sur la position de la limite Crétacé/Tertiaire. *Geobios* 14, 19–28 (in French).
- Guédé, K.É., Slimani, H., Louwye, S., Asebriy, L., Toufiq, A., Ahmamou, M., Hassani, I.-E.E.A.E., Digbehi, Z.B., 2014. Organic-walled dinoflagellate cysts from the Upper Cretaceous–lower Paleocene succession in the western External Rif, Morocco: New species and new biostratigraphic results. *Geobios* 47, 291–304.
- Guédé, K.É., Slimani, H., Yao, N.J.-P., Chekar, M., Koffi, N.J.-C., M'Hamdi, A., Mouah, R., Digbehi, Z.B., 2019. Late Cretaceous to Early Eocene dinoflagellate cysts from the “12 frères” borehole, Fresco, southwestern Côte d'Ivoire: Biostratigraphy and paleobiogeographic implication. *Journal of African Earth Sciences* 150, 744–756.
- Guerstein, G.R., Daners, G., 2004. Dinoflagelados del Maastrichtiense–Paleógeno en la Formación Gaviotín, Cuencas Punta del Este. *Cuencas Sedimentarias de Uruguay* 2, 37–70.
- Guerstein, G.R., Junciel, G.L., Guler, M. V., Daners, G., 2005. *Diconodinium lurensense* sp. nov., a late Maastrichtian to Danian dinoflagellate cyst from southwest Atlantic basins. *Ameghiniana* 42, 329–338.
- Guler, M.V., Borel, C.M., Brinkhuis, H., Navarro, E., Astini, R., 2014. Brackish to freshwater dinoflagellate cyst assemblages from the La Colonia Formation (Paleocene?), northeastern

- Patagonia, Argentina. *Ameghiniana* 51, 141–153.
- Guo Xianyu, Wang Daning, Ding Xiaozhong, Ye Liusheng, 2008. Discovery of dinoflagellate fossils in the Tuyiluo Formation of the Tarim Basin. *Geological Review* 54, 731–738 (in Chinese).
- Habib, D., 1972. Dinoflagellate stratigraphy Leg 11. Deep sea drilling project. In: Kaneps, A.G. (Ed.), *Deep Sea Drilling Project, Initial Reports 11*, U.S. Government Printing Office, Washington, pp. 367–425.
- Habib, D., Drugg, W.S., 1987. Palynology of sites 603 and 605, Leg 93, Deep Sea Drilling Project. In: Blakeslee, J.H., Whalen, E. (Eds.), *Deep Sea Drilling Project, Initial Reports 93*, U.S. Government Printing Office, Washington, pp. 751–775.
- Habib, D., Miller, J.A., 1989. Dinoflagellate species and organic facies evidence of marine transgression and regression in the Atlantic Coastal Plain. *Palaeogeography, Palaeoclimatology, Palaeoecology* 74, 23–47.
- Habib, D., Saeedi, F., 2007. The *Manumiella seelandica* global spike: Cooling during regression at the close of the Maastrichtian. *Palaeogeography, Palaeoclimatology, Palaeoecology* 255, 87–97.
- Habib, D., Eshet, Y., Van Pelt, R., 1994. Palynology of sedimentary cycles. In: Traverse, A. (Ed.), *Sedimentation of organic particles*. Cambridge University Press, Cambridge, pp. 311–335.
- Habib, D., Moshkovitz, S., Kramer, C., 1992. Dinoflagellate and calcareous nannofossil response to sea-level change in Cretaceous-Tertiary boundary sections. *Geology* 20, 165–168.
- Habib, D., Olsson, R.K., Chengie Liu, Moshkovitz, S., 1996. High-resolution biostratigraphy of sea-level low, biotic extinct and chaotic sedimentation at the Cretaceous-Tertiary boundary in Alabama, north of the Chicxulub Crater. *Geological Society of America, Special Papers* 307, 243–252.
- Hansen, H.J., Gwozdz, R., Hansen, J.M., Bromley, R., Rasmussen, K.L., 1986. The diachronous C-T plankton extinction in the Danish Basin. In: Walliser, O.H. (Ed.), *Global bio-events: lecture notes in earth science* 8. Springer, Berlin, pp. 381–384.
- Hansen, H.J., Rasmussen, K.L., Gwozdz, R., Hansen, J.M., Radwański, A., 1989. The Cretaceous/Tertiary boundary in Central Poland. *Acta Geologica Polonica* 39, 1–12.
- Hansen, J.M., 1977. Dinoflagellate stratigraphy and echinoid distribution in Upper Maastrichtian and Danian deposits from Denmark. *Bulletin of the Geological Society of Denmark* 26, 1–26.
- Hansen, J.M., 1979a. A new dinoflagellate zone at the Maastrichtian/Danian Boundary in Denmark. *Danmarks Geologiske Undersøgelse Årbog* 1978, 131–140.
- Hansen, J.M., 1979b. Dinoflagellate zonation around the boundary. In: Birkelund, T., Bromley, R.G. (Eds.), *Cretaceous-Tertiary boundary events symposium I. The Maastrichtian and Danian of Denmark*. University of Copenhagen, Copenhagen, pp. 136–143.
- Hargrove, D.C., Engelhardt, D.W., 1997. Palynology of the Maastrichtian/Danian boundary at Savannah River Site, South Carolina. *Sedimentary Geology* 108, 121–140.
- Hazel, J.E., Bybell, L.M., Christopher, R.A., Fredericksen, N.O., May, F.E., McLean, D.M., Poore, R.Z., Smith, C.C., Sohl, N.F., Valentine, P.C., Witmer, R.J., 1977. Biostratigraphy of the deep corehole, (Clubhouse Crossroads corehole 1), near Charleston, South Carolina. *United States Geological Survey, Professional Paper* 1028, 71–89.
- He Chengquan, 1991. Late Cretaceous-early Tertiary microphytoplankton from the western Tarim Basin in southern Xinjiang, China. *Nanjing Institute of Geology and Palaeontology, Academia Sinica*, 1–235, pls. 1–65 (in Chinese).
- Heilmann-Clausen, C., 1985. Dinoflagellate stratigraphy of the uppermost Danian to Ypresian in the Viborg I borehole, central Jylland, Denmark. *Danmarks Geologiske Undersøgelse, Serie A* 7, 1–69.
- Helby, R.J., Morgan, R., Partridge, A.D., 1987. A palynological zonation of the Australian Mesozoic; studies in Australian Mesozoic palynology. *Association of Australasian Palaeontologists, Memoir* 4, 1–94.
- Helenes, J., 1984. Dinoflagellates from Cretaceous to early Tertiary rocks of Sebastian Vizcaino Basin, Baja California, Mexico. *Society of Economic Paleontologists and Mineralogists Special Publication* 39, 80–106.
- Helenes, J., Cabrera, D., 2003. Oligocene–Miocene palynomorph assemblages from eastern Venezuela.

- Palynology 27, 5–25.
- Helenes, J., Somoza, D., 1999. Palynology and sequence stratigraphy of the Cretaceous of eastern Venezuela. *Cretaceous Research* 20, 447–463.
- Helenes, J., Téllez-Duarte, M.A., 2002. Paleontological evidence of the Campanian to early Paleocene paleogeography of Baja California. *Palaeogeography, Palaeoclimatology, Palaeoecology* 186, 61–80.
- Herngreen, G.F.W., Felder, W.M., Kedves, M., Meessen, J.P.M.T., 1986. Micropaleontology of the Maastrichtian in borehole Bunde, the Netherlands. *Review of Palaeobotany and Palynology* 48, 1–70.
- Herngreen, G.F.W., Schuurman, H.A.H.M., Verbeek, J.W., Brinkhuis, H., Burnett, J.A., Felder, W.M., Kedves, M., 1998. Biostratigraphy of Cretaceous/Tertiary boundary strata in the Curfs quarry, the Netherlands. *Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen TNO*, 61, 1–58.
- Hochuli, P., Kelts, K., 1977. Palynology of middle Cretaceous black clay facies from Deep Sea Drilling Project sites 417 and 418 of the western North Atlantic. In: Powell, R., Laughter, F. (Eds.), *Deep Sea Drilling Project, Initial Reports* 51–53, U.S. Government Printing Office, Washington, pp. 897–935.
- Hoek, R.P., Eshet, Y., Almogi-Labin, A., 1996. Dinoflagellate cyst zonation of Campanian–Maastrichtian sequences in Israel. *Micropaleontology* 42, 125–150.
- Hollis, C.J., Stickley, C.E., Bijl, P.K., Schiøler, P., Clowes, C.D., Xun Li, Campbell, H., 2017. The age of the Takatika Grit, Chatham Islands, New Zealand. *Alcheringa* 41, 383–396.
- Hultberg, S.U., 1985. Systematic paleontology. In: Hultberg, S.U. (Ed.), *Dinoflagellate studies of the upper Maastrichtian and Danian in southern Scandinavia* (Publ. PhD thesis). University of Stockholm, Stockholm, Sweden, pp. 104–189.
- Hultberg, S.U., 1986. Danian dinoflagellate zonation, the C-T boundary and the stratigraphical position of the fish clay in southern Scandinavia. *Journal of Micropalaeontology* 5, 37–47.
- Hultberg, S.U., Malmgren, B.A., 1987. Quantitative biostratigraphy based on late Maastrichtian dinoflagellates and planktonic foraminifera from southern Scandinavia. *Cretaceous Research* 8, 211–228.
- Iakovleva, A.I., Aleksandrova, G.N., 2013. To the question on dinocyst zonation of the Paleocene–Eocene deposits of western Siberia. *Moscow Society of Naturalists Bulletin, Geological Series* 88, 59–82 (in Russian).
- Ioannides, N.S., 1986. Dinoflagellate cysts from Upper Cretaceous–lower Tertiary section, Bylot and Devon islands, Arctic Archipelago. *Geological Survey of Canada, Bulletin* 371, 1–99.
- Jain, K.P., 1978. The Upper Cretaceous dinoflagellate assemblage from Vriddhachalam area, Cauvery Basin, south India. *The Palaeobotanist* 25, 146–160.
- Jain, K.P., Garg, R., 1986. Upper Paleocene dinoflagellate cysts and acritarchs from Vriddhachalam, Cauvery Basin, southern India. *Palaeontographica, Abteilung B* 198, 101–132, 6 pls.
- Jain, K.P., Millepied, P., 1973. Cretaceous microplankton from Senegal Basin, N. W. Africa. I. Some new genera, species and combinations of dinoflagellates. *The Palaeobotanist* 20, 22–32, pls. 1–3.
- Jan du Chêne, R.E., 1977. Palynostratigraphie (Maastrichtien–Éocène inférieur) des flyschs du Schlieren (Canton d’Obwald, Suisse centrale). *Revue de Micropaléontologie* 20, 147–156 (in French).
- Jan du Chêne, R.E., 1987. Étude systématique des kystes de dinoflagellés de la Formation des Madeleines (Danian du Sénégal). *Cahiers de Micropaléontologie, Nouv. Série* 2, 147–172, pls. 1–28 (in French).
- Jan du Chêne, R.E., Masure, E., Belcheler, I., Biffi, U., De Vains, G., Fauconnier, D., Ferrario, R., Foucher, J.-C., Gaillard, M., Hochuli, P., Lachkar, G., Michoux, D., Monteil, E., Moron, J.-M., Rauscher, R., Raynaud, J.-F., Taugourdeau, J., Turon, J.-L., 1986. Guide pratique pour la détermination de kystes de dinoflagellés fossiles: le complexe *Gonyaulacysta*. *Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine, Mémoire* 12, 1–479 (in French).
- Jaramillo, C.A., Rueda, M., Torres, V., 2011. A palynological zonation for the Cenozoic of the Llanos and Llanos Foothills of Colombia. *Palynology* 35, 46–84.
- Jbari, H., Slimani, H., Chekar, M., Asebriy, L., Benzaggagh, M., Mahboub, I., Chakir, S., 2020.

- Campanian to Danian dinoflagellate cyst assemblages from the southwestern Tethyan margin (Tattofte section, western External Rif, Morocco): Biostratigraphic and paleobiogeographic interpretations. *Review of Palaeobotany and Palynology* 279, 104225.
- Jurkowska, A., Barski, M., 2017. Maastrichtian island in the central European Basin—new data inferred from palynofacies analysis and inoceramid stratigraphy. *Facies* 63, 26.
- Jurkowska, A., Barski, M., Worobiec, E., 2019. The relation of a coastal environment to early diagenetic clinoptilolite (zeolite) formation - New data from the Late Cretaceous European Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology* 524, 166–182.
- Kasiński, J.R., Kramarska, R., Słodkowska, B., Sivkov, V., Piwocki, M., 2020. Paleocene and Eocene deposits on the eastern margin of the Gulf of Gdańsk (Yantarny P-1 borehole, Kaliningrad region, Russia). *Geological Quarterly* 64, 29–53.
- Kedves, M., 1992. Dél-Bakonyi növényi eredetű mikrofossziliák vizsgálata. *Öslénytani Viták (Discussiones Palaeontologicae)* 38, 47–57 (in Hungarian).
- Keller, G., Adatte, T., Berner, Z., Harting, M., Baum, G., Prauss, M., Tantawy, A., Stueben, D., 2007. Chicxulub impact predates K-T boundary: New evidence from Brazos, Texas. *Earth and Planetary Science Letters* 255, 339–356.
- Kenfack, P.L., Njike Ngaha, P.R., Ekodeck, G.E., Ngueutchoua, G., 2012. Fossils dinoflagellates from the northern border of the Douala sedimentary sub-basin (south-west Cameroon): Age assessment and paleoecological interpretations. *Geosciences* 2, 117–124.
- Kirsch, K.-H., 1991. Dinoflagellatenzysten aus der Oberkreide des Helvetikums und Nordultrahelvetikums von Oberbayern. *Münchner Geowissenschaftliche Abhandlungen, Reihe A, Geologie und Paläontologie* 22, 1–306.
- Kjellström, G., Hansen, J.M., 1981. Dinoflagellate biostratigraphy of the Cretaceous–Tertiary boundary in southern Scandinavia. *Geologiska Föreningens i Stockholm Förhandlingar* 103, 271–278.
- Köthe, A., 1991. Paleogene dinoflagellates from northwest Germany; biostratigraphy and paleoenvironment. *Geologisches Jahrbuch, Reihe A* 118, 3–111.
- Köthe, A., 2007. Cenozoic biostratigraphy from the German North Sea sector (G-11-1 borehole, dinoflagellate cysts, calcareous nannoplankton). *Zeitschrift der Dtsch. Gesellschaft für Geowissenschaften* 158, 287–327.
- Köthe, A., 2012. A revised Cenozoic dinoflagellate cyst and calcareous nannoplankton zonation for the German sector of the southeastern North Sea Basin. *Newsletters on Stratigraphy* 45, 189–220.
- Köthe, A., Khan, A.M., Ashraf, M., 1988. Biostratigraphy of the Surghar Range, Salt Range, Sulaiman Range and the Kohat area, Pakistan, according to Jurassic through Paleogene calcareous nannofossils and Paleogene dinoflagellates. *Geologisches Jahrbuch, Reihe B* 71, 3–87.
- Kuhn, W., Kirsch, K.-H., 1992. Eine Kreide/Tertiär-grenzprofil aus dem Helvetikum nördlich von Salzburg (Österreich). *Mitteilungen der Bayerischen Staatssammlung für Paläontologie und historische Geologie* 32, 23–35 (in German).
- Kurita, H., 2004. Paleogene dinoflagellate cyst biostratigraphy of northern Japan. *Micropaleontology* 50, 3–50.
- Kurita, H., McIntyre, D.J., 1995. Paleocene dinoflagellates from the Turtle Mountain Formation, southwestern Manitoba, Canada. *Palynology* 19, 119–136.
- Kurita, H., Obuse, A., 1997. Tertiary-Upper Cretaceous palynostratigraphy of the MITI Tempoku borehole, northern central Hokkaido. *Journal of Japanese Association of Petroleum Technology* 62, 13–24 (in Japanese).
- Laird, M.G., Bassett, K.N., Schiøler, P., Morgans, H.E.G., Bradshaw, J.D., Weaver, S.D., 2003. Paleoenvironmental and tectonic changes across the Cretaceous/Tertiary boundary at Tora, southeast Wairarapa, New Zealand: a link between Marlborough and Hawke's Bay. *New Zealand Journal of Geology and Geophysics* 46, 275–293.
- Lamolda, M.A., Shaozhi Mao, 1999. The Cenomanian–Turonian boundary event and dinocyst record at Ganuza (northern Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology* 150, 65–82.
- Landman, N.H., Johnson, R.O., Edwards, L.E., 2004a. Cephalopods from the Cretaceous/Tertiary

- boundary interval on the Atlantic Coastal Plain, with a description of the highest ammonite zones in North America. Part 1. Maryland and North Carolina. *American Museum Novitates* 3454, 1–64.
- Landman, N.H., Johnson, R.O., Edwards, L.E., 2004b. Cephalopods from the Cretaceous/Tertiary boundary interval on the Atlantic Coastal Plain, with a description of the highest ammonite zones in North America. Part 2. Northeastern Monmouth County, New Jersey. *Bulletin of the American Museum of Natural History* 287, 1–107.
- Landman, N.H., Johnson, R.O., Garb, M.P., Edwards, L.E., Kyte, F.T., 2007. Cephalopods from the Cretaceous/Tertiary boundary interval on the Atlantic Coastal Plain, with a description of the highest ammonite zones in North America. Part III. Manasquan River Basin, Monmouth County, New Jersey. *Bulletin of the American Museum of Natural History* 303, 1–122.
- Lange, D., 1969. Microplankton aus dem Fischton von Stevns-Klint auf Seeland. *Beiträge zur Meereskunde* 24–25, 110–121, 3 pls. (in German).
- Larina, E., Garb, M., Landman, N., Dastas, N., Thibault, N., Edwards, L., Phillips, G., Rovelli, R., Myers, C., Naujokaityte, J., 2016. Upper Maastrichtian ammonite biostratigraphy of the Gulf Coastal Plain (Mississippi Embayment, southern USA). *Cretaceous Research* 60, 128–151.
- Lebedeva, N.K., Aleksandrova, G.N., Shurygin, B.N., Ovechkina, M.N., Gnibidenko, Z.N., 2013. Paleontological and magnetostratigraphic data on Upper Cretaceous deposits from borehole no. 8 (Russkaya Polyana District, southwestern Siberia). *Stratigraphy and Geological Correlation* 21, 48–78.
- Lejeune-Carpentier, M., 1938. L'étude microscopique des silex. *Areoligera*: nouveau genre d'Hystrichosphaeridée. (Sixième note). *Annales de la Société Géologique de Belgique* 62, B163–B174 (in French).
- Lejeune-Carpentier, M., 1942. L'étude microscopique des silex. Péridiniens nouveaux ou peu connus. (Dixième note). *Annales de la Société géologique de Belgique* 65, B181–B192, 3 pls. (in French).
- Lejeune-Carpentier, M., Sarjeant, W.A.S., 1981. Restudy of some larger dinoflagellate cysts and an acritarch from the Upper Cretaceous of Belgium and Germany. *Annales de la Société géologique de Belgique* 104, 1–39.
- Lucas-Clark, J., 1987. *Wigginsiella* n. gen., *Spongodinium*, and *Apteodinium* as members of the *Aptiana-Ventriosum* complex (fossil Dinophyceae). *Palynology* 11, 155–184.
- Lucas-Clark, J., 2006. Small peridinioid dinoflagellate cysts from the Paleocene of South Carolina, U.S.A. *Palynology* 30, 183–210.
- Lucas, F.A., Ebahili, E.O., 2017. Lithofacies, palynology and paleoenvironmental study of Campanian to late Maastrichtian deposits of Ogbabu-1 well Anambra Basin, south eastern Nigeria. *Journal of Applied Sciences and Environmental Management* 21, 137–153.
- Lucas, F.A., Osezele, E.I., 2017. Sedimentology and palynological study of Maastrichtian to Danian sedimentary succession in Alo-1 Well, Anambra Basin. *International Journal of Engineering and Emerging Scientific Discovery* 2, 42–72.
- Luterbacher, H.P., Ali, J.R., Brinkhuis, H., Gradstein, F.M., Hooker, J.J., Monechi, S., Ogg, J.G., Powell, J., Röhl, U., Sanfilippo, A., Schmitz, B., 2004. The Paleogene Period. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.). *A geologic time scale 2004*. Cambridge University Press, Cambridge, pp. 384–408.
- Lyck, J.M., Stemmerik, L., 2000. Palynology and depositional history of the Paleocene? Thyra Ø Formation, Wandel Sea Basin, eastern North Greenland. *Geology of Greenland Survey Bulletin* 187, 21–49.
- M'Hamdi, A., Slimani, H., Ismail-Lattrache, K.B., Soussi, M., 2013. Biostratigraphie des kystes de dinoflagellés de la limite Crétacé-Paléogène à Ellès, Tunisie. *Revue de Micropaléontologie* 56, 27–42 (in French).
- M'Hamdi, A., Slimani, H., Louwye, S., Soussi, M., Ismail-Lattrache, K.B., Ali, W.B., 2015. Les kystes de dinoflagelles et palynofacies de la transition Maastrichtien–Danien du stratotype El kef (Tunisie). *Comptes Rendus Palevol* 14, 167–180 (in French).
- Machalski, M., Vellekoop, J., Dubicka, Z., Peryt, D., Harasimiuk, M., 2016. Late Maastrichtian

- cephalopods, dinoflagellate cysts and foraminifera from the Cretaceous–Paleogene succession at Lechówka, southeast Poland: stratigraphic and environmental implications. *Cretaceous Research* 57, 208–227.
- Mahboub, I., Slimani, H., Toufiq, A., Chekar, M., Djeya, K.L., Jbari, H., Chakir, S., 2019. Middle Eocene to early Oligocene dinoflagellate cyst biostratigraphy and paleoenvironmental interpretations of the Ben Attaya section at Taza, eastern External Rif, Morocco. *Journal of African Earth Sciences* 149, 154–169.
- Margielewski, W., Jankowski, L., Krąpiec, M., Garecka, M., Hałas, S., Urban, J., 2017. Analysis of reworked sediments as a basis of the Palaeogene–Neogene palaeogeography reinterpretation: Case study of the Roztocze region (SE Poland). *Sedimentary Geology* 352, 14–29.
- Marheinecke, U., 1992. Monographie der Dinozysten, Acritarcha und Chlorophyta des Maastrichtium von Hemmoor (Niedersachsen). *Palaeontographica, Abteilung B* 227, 1–173, 30 pls. (in German).
- Masure, E., Rauscher, R., Dejax, J., Schuler, M., Ferré, B., 1998. Cretaceous–Paleocene palynology from the Côte d'Ivoire-Ghana Transform Margin, site 959, 960, 961, and 962. In: Mascare, J., Lohmann, G.P., Moullade, M. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results* 159, College Station, Texas, pp. 253–276.
- Mavrides, A., Ioakim, C., Skourtsis-Coroneou, V., 1994. Age du Flysch d'Aetolie, Natpaktie, Greece. *Comptes Rendus de l'Académie des Sciences, Série IIA* 318, 1255–1260 (in French).
- May, F.E., 1980. Dinoflagellate cysts of the Gymnodiniaceae, Peridiniaceae, and Gonyaulacaceae from the Upper Cretaceous Monmouth Group, Atlantic Highlands, New Jersey. *Palaeontographica, Abteilung B* 172, 10–116, 23 pls.
- McIntyre, J. D., 1999. Campanian to Paleocene dinoflagellate assemblages from the Turtle Mountain core hole, Manitoba, western Canada. *Canadian Journal of Earth Sciences* 36, 769–774.
- McLachlan, S.M.S., Pospelova, V., Hebda, R.J., 2018. Dinoflagellate cysts from the upper Campanian (Upper Cretaceous) of Hornby Island, British Columbia, Canada, with implications for Nanaimo Group biostratigraphy and paleoenvironmental reconstructions. *Marine Micropaleontology* 145, 1–20.
- McMinn, A., 1988. Outline of a Late Cretaceous dinoflagellate zonation of northwestern Australia. *Alcheringa* 12, 137–156.
- Mehrotra, N.C., Sarjeant, W.A.S., 1987. Late Cretaceous to early Tertiary dinoflagellate cysts from Narasapur Well-1, Godavari-Krishna Basin, south India. *Geobios* 20, 149–191.
- Mehrotra, N.C., Singh, K., 2003. Atlas of dinoflagellate cysts from Mesozoic–Tertiary sediments of Krishna-Godavari Basin. Volume II. Tertiary dinoflagellate cysts. *Palaeontographica Indica*, Keshava Deva Malaviya Institute of Petroleum Exploration, Oil and Natural Gas Corporation Special Publication 8, 1–134, 36 pls.
- Misra, C.M., Kumar, A., Prasad, B., Pundir, B.S., Saxena, R.K., 1994. A note on the bioevents across the K/T Transition in the well Modi-A, Krishna-Godavari Basin, India. *Geoscience Journal* 15, 33–36.
- Mohamed, O., Wagreich, M., 2013. Organic-walled dinoflagellate cyst biostratigraphy of the Well Höflein 6 in the Cretaceous–Paleogene Rhenodanubian Flysch Zone (Vienna Basin, Austria). *Geological Carpathica* 64, 209–230.
- Mohamed, O., Mahdy, F., Tahoun, S.S., 2019. Dinoflagellate cyst biostratigraphy of the Santonian–Oligocene succession of the Drazia-1 well, north Western Desert, Egypt. *Journal of African Earth Sciences* 158, 103511.
- Mohamed, O., Piller, W.E., Egger, H., 2012. The dinocyst record across the Cretaceous/Palaeogene boundary of a bathyal mid-latitude Tethyan setting: Gosau Group, Gams Basin, Austria. *Cretaceous Research* 35, 143–168.
- Mohamed, O., Piller, W.E., Egger, H., 2013. Dinoflagellate cysts and palynofacies across the Cretaceous/Palaeogene boundary at the neritic Waidach Section (Eastern Alps, Austria). *Review of Palaeobotany Palynology* 190, 85–103.
- Mohsen, A., Ghasemi-Nejad, E., 2008. Palynology and paleoenvironment of the Neysar Formation in the sedimentary basin east of Kopet Dag. *Journal of Science, University of Tehran* 32, 173–185 (in

- Persian).
- Molina, E., Alegret, L., Arenilla, I., Arz, J.A., Gallala, N., Hardenbol, J., Von Salis, K., Steurbaut, E., Vandenbelghe, N., Zaghib-Turki, D., 2006. The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, “Tertiary”, Cenozoic) at El Kef, Tunisia — Original definition and revision. *Episodes* 29, 263–273.
- Morgan, R., Rowett, A., White, M.R., 2003. Biostratigraphy. In: O’Brien, G.W., Paraschivoiu, E., Hibbert, J.E. (Eds.), *Petroleum geology of South Australia (volume 5): Great Australian Bight*. Department of Primary Industries and Resources, Adelaide, South Australia, pp. 1–46.
- Morgenroth, P., 1968. Zur Kenntnis der Dinoflagellaten und Hystrichosphaeridien des Danien. *Geologisches Jahrbuch* 86, 533–577 (in German).
- Morton, A.C., Evans, D., Harland, R., King, C., Ritchie, D.K., 1988. Volcanic ash in a cored borehole W of the Shetland Islands: evidence for Selandian (late Palaeocene) volcanism in the Faeroes region. *Geological Society, London, Special Publications* 39, 263–269.
- Moshkovitz, S., Habib, D., 1993. Calcareous nannofossil and dinoflagellate stratigraphy of the Cretaceous-Tertiary boundary, Alabama and Georgia. *Micropaleontology* 39, 167–191.
- Mudge, D.C., Jones, S.M., 2004. Palaeocene uplift and subsidence events in the Scotland–Shetland and North Sea region and their relationship to the Iceland Plume. *Journal of the Geological Society, London* 161, 381–386.
- Naeher, S., Hollis, C.J., Clowes, C.D., Ventura, G.T., Shepherd, C.L., Crouch, E.M., Morgans, H.E.G., Bland, K.J., Strogon, D.P., Sykes, R., 2019. Depositional and organofacies influences on the petroleum potential of an unusual marine source rock: Waipawa Formation (Paleocene) in southern East Coast Basin, New Zealand. *Marine and Petroleum Geology* 104, 468–488.
- Nagy, J., Kaminski, M.A., Gradstein, F.M., Johnson, K., 2004. Quantitative foraminiferal and palynomorph biostratigraphy of the Paleogene in the southwestern Barents Sea. *Grzybowski Foundation, Special Publication* 8, 359–379.
- Naqshabandi, F.S., 2018. Palynological study of Kolosh Formation (Paleocene–early Eocene) in Dokan area, Sulaimani, Kurdistan region, Iraq. *Tikrit Journal of Pure Science* 23, 48–57.
- Neumann, M., Bellier, J.-P., Damotte, R., Lambert, B., Masure, E., Monciardini, C., Platel, J.P., Andreieff, P., 1983. Le Campanien stratotypique: étude lithologique et micropaléontologique. *Géologie Méditerranéenne* 10, 41–57 (in French).
- Niechwedowicz, M., 2019. *Odontochitina dilatata* sp. nov. from the Campanian (Upper Cretaceous) of Poland: the importance of wall structure in the taxonomy of selected ceratiacean dinoflagellate cysts. *Palynology* 43, 423–450.
- Nøhr-Hansen, H., 1994. Dinoflagellate cyst biostratigraphy of the Upper Cretaceous black mudstones between Niaqornat and Ikorfat of the north coast of Nuussuaq West Greenland. *Grønlands Geologiske Undersøgelse, Open File Series* 94/14, 1–24.
- Nøhr-Hansen, H., 1996. Upper Cretaceous dinoflagellate cyst stratigraphy, onshore West Greenland. *Grønlands Geologiske Undersøgelse, Bulletin* 170, 1–104.
- Nøhr-Hansen, H., 2012. Palynostratigraphy of the Cretaceous–lower Palaeogene sedimentary succession in the Kangerlussuaq Basin, southern East Greenland. *Review of Palaeobotany and Palynology* 178, 59–90.
- Nøhr-Hansen, H., Dam, G., 1997. Palynology and sedimentology across a new marine Cretaceous–Tertiary boundary section on Nuussuaq, West Greenland. *Geology* 25, 851–854.
- Nøhr-Hansen, H., Nielsen, L.H., Sheldon, E., Hovikoski, J., Alsen, P., 2011. Palaeogene deposits in north-east Greenland. *Geological Survey of Denmark and Greenland Bulletin* 23, 61–64.
- Norris, R.D., Firth, J.V., 2002. Mass wasting of Atlantic continental margins following the Chicxulub impact event. *Geological Society of America, Special Papers* 356, 79–95.
- Norris, R.D., Firth, J., Blusztajn, J.S., Rivizza, G., 2000. Mass failure of the North Atlantic margin triggered by the Cretaceous–Paleogene bolide impact. *Geology* 28, 1119–1122.
- Oboh-Ikuenobe, F.E., Antolinez-Delgado, H., Awad, W.K., 2017. Dinoflagellate cyst assemblages, biostratigraphy and paleoenvironment of a Paleocene–early Eocene sedimentary succession in the

- northern Niger Delta Basin: Comparison with low, mid and high latitude regions. *Palaeogeography, Palaeoclimatology, Palaeoecology* 481, 29–43.
- Oboh-ikuenobe, F.E., Spencer, M.K., Campbell, C.E., Haselwander, R.D., 2012. A portrait of late Maastrichtian and Paleocene palynoflora and paleoenvironment in the northern Mississippi Embayment, southeastern Missouri. *Palynology* 36, 63–79.
- Oloto, I.N., 1989. Maastrichtian dinoflagellate cyst assemblage from the Nkporo Shale on the Benin Flank of the Niger Delta. *Review of Palaeobotany and Palynology* 57, 173–186.
- Olsson, R.K., Miller, K.G., Browning, J. V, Habib, D., Sugarman, P.J., 1997. Ejecta layer at the Cretaceous-Tertiary boundary, Bass River, New Jersey (Ocean Drilling Program Leg 174AX). *Geology* 25, 759–762.
- Oreshkina, T.V, Aleksandrova, G.N., 2007. Terminal Paleocene of the Volga middle reaches: biostratigraphy and paleosettings. *Stratigraphy and Geological Correlation* 15, 206–230.
- Oreshkina, T. V, Yakovleva, A.I., Aleksandrova, G.N., 2008. A direct correlation of the zonal scales of the boreal Paleogene by diatoms and dinocysts (based on materials from well 19, Ust-Magnya, eastern slope of the Northern Urals). *News of Paleontology and Stratigraphy* 10–11, 347–350 (in Russian).
- Palamarczuk, S., Ambrosini, G., Villar, H., Medina, F., Martínez Macchiavello, J.C., Rinaldi, C.A., 1984. Las formaciones López de Bertodano y Sobral en la Isla Vicecomodoro Marambio, Antártida. *Noveno Congreso Geológico Argentina, San Carlos de Bariloche, Actas 1*, 399–419 (in Spanish).
- Palynodata Inc., White, J.M., 2008. Palynodata Datafile: 2006 version with introduction by J.M. White. Geological Survey of Canada, Open File 5793.
- Papú, O.H., Prámparo, M.B., Náñez, C., Concheyro, A., 1999. Palinología y micropaleontología de la Formación Jaguel (Maastrichtian–Daniano), Perfil Opasso, Cuenca Neuquina, Argentina. *Simposio Paleogeno de América del Sur (Buenos Aires, 1996), Actas Subsecretaria de Minería de la Nación, Anales 33*, 17–31 (in Spanish).
- Partridge, A.D., 2008. Interpretative data. Palynological analysis of cuttings samples between 1440 and 3030 metres in Jarver-1, offshore Sorell Basin. *Biostrata Report* 2008/06A, 1–20.
- Pascher, A., 1914. Über flagellaten und algen. *Deutsche Botanische Gesellschaft, Berichte* 32, 136–160 (in German).
- Pearson, P.N., Nicholas, C.J., Singano, J.M., Bown, P.R., Coxall, H.K., Van Dongen, B.E., Huber, B.T., Karega, A., Lees, J.A., MacLeod, K., McMillan, I.K., Pancost, R.D., Pearson, M., Msaky, E., 2006. Further Paleogene and Cretaceous sediment cores from the Kilwa and Lindi areas of coastal Tanzania: Tanzania Drilling Project sites 6–10. *Journal of African Earth Sciences* 45, 279–317.
- Pedersen, G.K., Nøhr-Hansen, H., 2014. Sedimentary successions and palynoevent stratigraphy from the non-marine Lower Cretaceous to the marine Upper Cretaceous of the Nuussuaq Basin, West Greenland. *Bulletin of Canadian Petroleum Geology* 62, 261–288.
- Peng Shifu. 1992. Tertiary transgressive sequences and stratigraphic correlation in China offshore area. *Marine Geology and Quaternary Geology* 12, 41–56 (in Chinese).
- Pervushov, E.M., Seltser, V.B., Benyamovskiy, V.N., Aleksandrova, G.N., Kalyakin, E.A., Vishnevskaya, V.S., Kopaevich, L.F., Akhlestina, E.F., Ovechkina, M.N., 2015. Biostratigraphic subdivision of Kokurino section (Saratov region) and some aspects of Campanian stratigraphy in Middle Volga. *Bulletin of the Moscow Institute of Applied Mathematics* 2, 51–84 (in Russian).
- Pirrie, D., Crame, J.A., Lomas, S.A., Riding, J.B., 1997. Late Cretaceous stratigraphy of the Admiralty Sound region, James Ross Basin, Antarctica. *Cretaceous Research* 18, 109–137.
- Pocknall, D.T., Erlich, R.N., 2020. Palynostratigraphy and lithostratigraphy of Upper Cretaceous and Paleogene outcrop sections, Mérida Andes (Maracaibo Basin), western Venezuela. *Journal of South American Earth Sciences* 104, 102830.
- Pocknall, D.T., Tremain, R., 1988. Tour LB1, 7th International Palynological Conference, Brisbane, Australia, August, 1988. New Zealand palynology and paleobotany: A field guide to palynological and paleobotanical localities. *New Zealand Geological Survey Record* 33, 1–107.
- Pocknall, D.T., Erlich, R.N., Stein, J.A., Lorente, M.A., 2001. The palynofloral succession across the

- Cretaceous to Paleocene transition zone, Merida Andes, western Venezuela. In: Goodman, D.K., Clarke, R.T. (Eds.), *Proceedings of the 9th International Palynological Congress*, Houston, Texas, U.S.A., 1996. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 171–179.
- Portnyagina, L.A., 1971. Palynology of the upper Senonian and Paleogene deposits from the Skibovoy Zone of the Carpathians. In: Zеров, D.K. (Ed.), *3rd International Palynological Conference* (Novosibirsk, July 19–25). Problems of Palynology. Naukova Dumka, Kiev, pp. 110–117 (in Russian).
- Powell, A.J., 1992. Dinoflagellate cysts of the Tertiary system. In: Powell, A.J. (Ed.), *A stratigraphic index of dinoflagellate cysts*. British Micropaleontological Society Publication Series, Chapman and Hall, London, 155–229, pls. 4.1–4.11.
- Prámparo, M.B., Papú, O.H., 2006. Late Maastrichtian dinoflagellate cysts from the Cerro Butaló section, southern Mendoza province, Argentina. *Journal of Micropalaeontology* 25, 23–33.
- Prasad, B., 1999. Palynological characterisation, biostratigraphy and depositional environment of pre-Tertiary lithounits of Krishna-Godavari Basin, India. *Geoscience Journal* 20, 143–164.
- Prasad, B., Pundir, B.S., 2020. Gondwana biostratigraphy and geology of West Bengal Basin, and its correlation with adjoining Gondwana basins of India and western Bangladesh. *Journal of Earth System Science* 129, 22.
- Prauss, M.L., 2009. The K/Pg boundary at Brazos-River [sic], Texas, USA — An approach by marine palynology. *Palaeogeography, Palaeoclimatology, Palaeoecology* 283, 195–215.
- Prauss, M.L., 2015. Marine palynology of the Oceanic Anoxic Event 3 (OAE3, Coniacian–Santonian) at Tarfaya, Morocco, NW Africa—transition from preservation to production controlled accumulation of marine organic carbon. *Cretaceous Research* 53, 19–37.
- Premaor, E., Souza, P.A., Ferreira, E.P., Guerstein, G.R., Arai, M., 2018. Palinotaxonomia da seção Cretácea a Neogena da Bacia de Pelotas, Brasil: cistos de dinoflagelados das ordens Ptychodiscales e Gonyaulacales. *Pesquisas em Geociências* 45, e647 (in Portuguese).
- Prévôt, L., Lucas, J., Doubinger, J., 1979. Une correspondance entre le contenu palynologique et la composition minéralogique et chimique d'une série phosphatée sédimentaire (Ganntour, Maroc). *Sciences Géologiques, Bulletin* 32, 69–90 (in French).
- Přikryl, T., Skupien, P., 2013. Some new Eocene elasmobranch reports from the Outer Western Carpathians (Moravia, Czech Republic). *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 268, 113–123.
- Prowell, D.C., Edwards, L.E., Frederiksen, N.O., 1985. The Ellenton Formation in South Carolina—a revised age designation from Cretaceous to Paleocene. *United States Geological Survey, Bulletin* 1605-A, A63–A69.
- Quattrocchio, M.E., 2009. Paleogene dinoflagellate cysts from Punta Prat, southern Chile. *Palynology* 33, 141–156.
- Quattrocchio, M.E., Sarjeant, W.A.S., 2003. Dinoflagellates from the Chorrillo Chico Formation (Paleocene) of southern Chile. *Ameghiniana* 40, 129–153.
- Rabbani, J., Ghasemi-Nejad, E., Ashoir, A., Vahidinia, M., 2015. Quantitative palynostratigraphy and palaeoecology of Tethyan Paleocene–Eocene red beds in north of Zagros sedimentary basin, Iran. *Arabian Journal of Geosciences* 8, 827–838.
- Raine, J.I., Schiøler, P., 2012. Upper Cretaceous biostratigraphy of Maui-4 and Tane-1 wells, Taranaki Basin. *Institute of Geological and Nuclear Sciences, Science Report* 2012/28, 1–61.
- Raju, D.S.N., Jaiprakash, B.C., Kumar, A., Saxena, R.K., Dave, A., Chatterjee, T.K., Mishra, C.M., 1995. Age of Deccan volcanism across KTB in Krishna-Godavari Basin: new evidences. *Journal of the Geological Society of India* 45, 229–233.
- Rauscher, R., Doubinger, J., 1982. Les dinokystes du Maastrichtien phosphaté au Maroc. *Sciences Géologiques, Bulletin* 35, 97–116 (in French).
- René, B.G., Digbehi, Z.B., Raphael, Y.K., Juliette, T.-Y., David, K.K., Ignacec, T., 2012. Stratigraphie palynologique du Maastrichtien supérieur-Eocène supérieur du bassin sédimentaire offshore de Côte

- d'Ivoire, Afrique de l'Ouest. *International Journal of African Studies* 6, 40–57 (in French).
- Roncaglia, L., Corradini, D., 1997. Upper Campanian to Maastrichtian dinoflagellate zonation in the northern Apennines, Italy. *Newsletters on Stratigraphy* 35, 29–57, pls. 1–2.
- Roncaglia, L., Field, B.D., Raine, J.I., Schiøler, P., Wilson, G.J., 1999. Dinoflagellate biostratigraphy of Piripauan–Haumurian (Upper Cretaceous) sections from northeast South Island, New Zealand. *Cretaceous Research* 20, 271–314.
- Salamon, M.A., Gorzelak, P., Ferré, B., Lach, R., 2010. Roveacrinids (Crinoidea, Echinodermata) survived the Cretaceous–Paleogene (K–Pg) extinction event. *Geology* 38, 883–885.
- Sánchez, A., Pavlishina, P., Godoy, E., Hervé, F., Fanning, C.M., 2010. On the presence of upper Paleocene rocks in the foreland succession at Cabo Nariz, Tierra del Fuego, Chile: geology and new palynological and U–Pb data. *Andean Geology* 37, 413–432.
- Sánchez-Pellicer, R., Masure, E., Villier, L., 2017. A new biostratigraphic correlation for Late Cretaceous–Paleocene strata of the Gulf of Guinea: Evidence from dinoflagellate cysts. *Comptes Rendus Geoscience* 349, 32–41.
- Sarkis, M.F.R., Arai, M., Koutsoukos, E.A.M., 2002. Dinoflagelados do limite Cretáceo-Terciário (K–T), Pedreira Poty, Bacia de Pernambuco-Paraíba, nordeste do Brasil. In: Castro, J. C. (Ed.), *Boletim do 4th Simpósio sobre o Cretáceo do Brasil; 2nd Simpósio sobre o Cretáceo do América del Sur* (São Pedro, Brasil, July 31). Universidade Estadual Paulista, Rio Claro, pp. 271–277 (in Portuguese).
- Scasso, R.A., Prámparo, M.B., Vellekoop, J., Franzosi, C., Castro, L.N., Sinninghe Damsté, J.S., 2020. A high-resolution record of environmental changes from a Cretaceous–Paleogene section of Seymour Island, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology* 555, 109844.
- Schellenberg, S.A., Brinkhuis, H., Stickley, C.E., Fuller, M., Kyte, F.T., Williams, G.L., 2004. The Cretaceous/Paleogene transition on the East Tasman Plateau, southwestern Pacific. In: Exxon, N.F., Kennett, J.P., Malone, M.J. (Eds.), *The Cenozoic Southern Ocean: Tectonics, sedimentation and climate change between Australia and Antarctica*. American Geophysical Union, *Geophysical Monograph* 151, pp. 93–112.
- Schiøler, P., Wilson, G.J., 1993. Maastrichtian dinoflagellate zonation in the Dan Field, Danish North Sea. *Review of Palaeobotany and Palynology* 78, 321–351.
- Schiøler, P., Brinkhuis, H., Roncaglia, L., Wilson, G.J., 1997. Dinoflagellate biostratigraphy and sequence stratigraphy of the Type Maastrichtian (Upper Cretaceous), ENCI Quarry, The Netherlands. *Marine Micropaleontology* 31, 65–95.
- Schiøler, P., Andsbjerg, J., Clausen, O.R., Dam, G., Dybkjær, K., Hamberg, L., Heilmann-Clausen, C., Johannessen, E.P., Kristensen, L.E., Prince, I., Rasmussen, J.A., 2007. Lithostratigraphy of the Palaeogene–lower Neogene succession of the Danish North Sea. *Geological Survey of Denmark and Greenland, Bulletin* 12, 1–77.
- Schröder, T., 1992. A palynological zonation for the Paleocene of the North Sea Basin. *Journal of Micropalaeontology* 11, 113–126.
- Schumacker-Lambry, J., 1977. Microfossiles végétaux ?planctoniques. In: Streel, M., Bick, H., Fairon-Demaret, M., Schumacker-Lambry, J., Vanguetaine, M. (Eds.), *Macro- et microfossiles végétaux dans le contexte litho- et biostratigraphique du Senonien–Paléocène de la rive gauche de la Meuse au nord de Liège, Belgique. Livret-guide de l'excursion du 22 septembre 1977 à l'occasion du symposium 'Apport des techniques récentes en Palynologie'*. Université de Liège, Liège, pp. 49–53, pls. 1–7 (in French).
- Schumacker-Lambry, J., Chateauneuf, J.-J., 1976. Dinoflagellés et acritarches des marnes Heersiennes de Gelinden (base du Landénien, Paléocène, Belgique). *Review of Palaeobotany and Palynology* 21, 267–294 (in French).
- Shaozhi Mao, Norris, G., 1984. Dinoflagellate and acritarch stratigraphy (Late Cretaceous and early Tertiary) western Talimu Basin, Xinjiang Autonomous Region, northwestern China. *Earth Science, Journal of Wuhan College of Geology* 2, 7–22 (in Chinese).
- Sharafutdinova, N.G., 1992. Dinocysts at the Maastrichtian–Danian boundary in Kishak section (Mangyshlak). *Moscow Society of Naturalists Bulletin, Geological Series* 67, 92–98 (in Russian).

- Shcherbinina, E.A., Aleksandrova, G.N., Iakovleva, A.I., Stupin, S.I., Zakrevskaya, E.Y., 2014. Microbiota and stratigraphy of lower Paleogene deposits of the Urma Plateau, central Dagestan. *Stratigraphy and Geological Correlation* 22, 61–95.
- Skupien, P., Mohamed, O., 2008. Campanian to Maastrichtian palynofacies and dinoflagellate cysts of the Silesian Unit, Outer Western Carpathians, Czech Republic. *Bulletin of Geosciences* 83, 207–224.
- Skupien, P., Bubík, M., Švábenická, L., Mikuláš, R., Vašíček, Z., Matýsik, D., 2009. Cretaceous oceanic red beds in the Outer Western Carpathians, Czech Republic. *Society of Economic Paleontologists and Mineralogists Special Publication* 91, 99–109.
- Slimani, H., 1994. Les dinokystes des craies du Campanien au Danien à Halembaye, Turnhout (Belgique) et à Beutenaken (Pays-Bas). *Mémoires pour servir à l'Explication des Cartes Géologiques et Minières de la Belgique* 37, 1–173 (in French).
- Slimani, H., 2000. Nouvelle zonation aux kystes de dinoflagellés du Campanien au Danien dans le nord et l'est de la Belgique et dans le sud-est des Pays-Bas. *Memoirs of the Geological Survey of Belgium* 46, 1–88 (in French).
- Slimani, H., 2001. Les kystes de dinoflagellés du Campanien au Danien dans la région de Maastricht (Belgique, Pays-Bas) et de Turnhout (Belgique): biozonation et corrélation avec d'autres régions en Europe occidentale. *Geologica et Palaeontologica* 35, 161–201 (in French).
- Slimani, H., Toufiq, A., 2013. A Cretaceous–Palaeogene boundary geological site, revealed by planktic foraminifera and dinoflagellate cysts, at Ouled Haddou, eastern external Rif Chain, Morocco. *Journal of African Earth Sciences* 88, 38–52.
- Slimani, H., Louwye, S., Toufiq, A., 2010. Dinoflagellate cysts from the Cretaceous–Paleogene boundary at Ouled Haddou, southeastern Rif, Morocco: biostratigraphy, paleoenvironments and paleobiogeography. *Palynology* 34, 90–124.
- Slimani, H., Louwye, S., Toufiq, A., 2012. New species of organic-walled dinoflagellate cysts from the Maastrichtian–Danian boundary interval at Ouled Haddou, northern Morocco. *Alcheringa* 36, 337–353.
- Slimani, H., Louwye, S., Duser, M., Lagrou, D., 2011. Connecting the Chalk Group of the Campine Basin to the dinoflagellate cyst biostratigraphy of the Campanian to Danian in borehole Meer (northern Belgium). *Geologie en Mijnbouw* 90, 129–164.
- Slimani, H., Guédé, K.É., Williams, G.L., Asebriy, L., Ahmamou, M., 2016. Campanian to Eocene dinoflagellate cyst biostratigraphy from the Tahar and Sekada sections at Arba Ayacha, western External Rif, Morocco. *Review of Palaeobotany and Palynology* 228, 26–46.
- Slimani, H., Mahboub, I., Toufiq, A., Jbari, H., Chakir, S., Tahiri, A., 2019. Bartonian to Priabonian dinoflagellate cyst biostratigraphy and paleoenvironments of the M'karcha section in the Southern Tethys margin (Rif Chain, Northern Morocco). *Marine Micropaleontology* 153, 101785.
- Slimani, H., M'Hamdi, A., Uchman, A., Gasiński, M.A., Guédé, K.É., Mahboub, I., 2021b. Dinoflagellate cyst biostratigraphy of Upper Cretaceous turbiditic deposits from a part of the Bąkowiec section in the Skole Nappe (Outer Carpathians, southern Poland). *Cretaceous Research*, 104780.
- Slimani, H., Benam, V.M., Țabără, D., Aassoumi, H., Jbari, H., Chekar, M., Mahboub, I., M'Hamdi, A., 2021a. Distribution of dinoflagellate cyst assemblages and palynofacies in the Upper Cretaceous deposits from the neritic Bou Lila section, External Rif (northwestern Morocco): Implications for the age, biostratigraphic correlations and paleoenvironmental reconstructions. *Marine Micropaleontology* 162, article 101951.
- Słodkowska, B., 2003. Wstępne dane o badaniach fitoplanktonu w Kamiennym Dole (okolice Kazimierza Dolnego). *Przegląd Geologiczny* 51, 1075–1078 (in Polish).
- Słodkowska, B., 2009. Palynology of the Palaeogene and Neogene from the Warmia and Mazury areas (NE Poland). *Geologos* 15, 219–234.
- Słodkowska, B., Gałazka, D., 2015. Osady Paleogenu i Neogenu w wielkoskalowych strukturach glacytektonicznych Wzgórz Dylewskich. *Biuletyn Państwowego Instytutu Geologicznego* 461, 251–294 (in Polish).

- Sluijs, A., Van Rooij, L., Frieling, J., Laks, J., Reichart, G.-J., 2018. Single-species dinoflagellate cyst carbon isotope ecology across the Paleocene-Eocene Thermal Maximum. *Geology* 46, 79–82.
- Smit, J., Brinkhuis, H., 1996. The Geulhemmerberg Cretaceous/Tertiary boundary section (Maastrichtian type area, SE Netherlands); summary of results and a scenario of events. *Geology en Mijnbouw* 75, 283–293.
- Smith, R., Møller, N., 2003. Sedimentology and reservoir modelling of the Ormen Lange field, mid Norway. *Marine and Petroleum Geology* 20, 601–613.
- Soliman, A., Fensome, R.A., 2019. New insights on the morphology and occurrence of the Palaeogene dinoflagellate cyst species *Duosphaeridium rugosum* and on the taxonomic affinity of the genus *Duosphaeridium*. *Journal of Systematic Palaeontology* 17, 1519–1531.
- Soliman, A., Slimani, H., 2019. The Cretaceous–Paleogene (K/Pg) boundary in the Dababiya Borehole, southern Egypt: An organic-walled dinoflagellate cyst approach. *Cretaceous Research* 98, 230–249.
- Soliman, A., Suttner, T.J., Lukeneder, A., Summesberger, H., 2009. Dinoflagellate cysts and ammonoids from Upper Cretaceous sediments of the Pemberger Formation (Krappfeld, Carinthia, Austria). *Annalen des Naturhistorischen Museums in Wien, Serie A* 110, 401–421.
- Sønderholm, M., Nøhr-hansen, H., Bojesen-koefoed, J., Dalhoff, F., Rasmussen, J.A., 2003. Regional correlation of Mesozoic–Palaeogene sequences across the Greenland–Canada boundary. *Danmarks og Grønlands Geologiske Undersøgelse, Rapport*, 2003/25, 184 pp., 1 CD-ROM.
- Stanley, E.A., 1965. Upper Cretaceous and Paleocene plant microfossils and Paleocene dinoflagellates and hystrichosphaerids from northwestern South Dakota. *Bulletins of American Paleontology* 49, 179–384.
- Steeman, T., De Weirtdt, J., Smith, T., De Putter, T., Mees, F., Louwye, S., 2020. Dinoflagellate cyst biostratigraphy and palaeoecology of the early Paleogene Landana reference section, Cabinda Province, Angola. *Palynology* 44, 280–309.
- Stone, J.F., 1973. Palynology of the Almond Formation, (Upper Cretaceous), Rock Springs Uplift, Wyoming. *Bulletins of American Paleontology* 64, 1–135.
- Stover, L.E., 1973. Paleocene and Eocene species of *Deflandrea* (Dinophyceae) in Victorian coastal and offshore basins, Australia. *Geological Society of Australia, Special Publication* 4, 167–188, 5 pls.
- Stover, L.E., Evitt, W.R., 1978. Analyses of pre-Pleistocene organic-walled dinoflagellates. *Stanford University Publications, Geological Sciences* 15, 300 pp.
- Stover, L.E., Brinkhuis, H., Damassa, S.P., de Verteuil, L., Helby, R.J., Monteil, E., Partridge, A.D., Powell, A.J., Riding, J.B., Smelror, M., Williams, G.L., 1996. Mesozoic–Tertiary dinoflagellates, acritarchs and prasinophytes. In: *Palynology: principles and applications*, volume 3. Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 641–750.
- Strong, C.P., Hollis, C.J., Wilson, G.J., 1995. Foraminiferal, radiolarian, and dinoflagellate biostratigraphy of Late Cretaceous to middle Eocene pelagic sediments (Muzzle Group), Mead Stream, Marlborough, New Zealand. *New Zealand Journal of Geology and Geophysics* 38, 171–212.
- Sung Zhichen, He Chengquan, Qian Zeshu, Pan Zhaorin, Zheng Guoguang, Zheng Yuefang, 1978. On the Paleogene dinoflagellates and acritarchs from the coastal region of Bohai. *Nanjing Institute of Geology and Paleontology, Academia Sinica, Nanjing, China*, 190 pp., 49 pls. (in Chinese).
- Surlyk, F., Rasmussen, S.L., Boussaha, M., Schiøler, P., Schovsbo, N.H., Sheldon, E., Stemmerik, L., Thibault, N., 2013. Upper Campanian–Maastrichtian holostratigraphy of the eastern Danish Basin. *Cretaceous Research* 46, 232–256.
- Țabără, D., Slimani, H., 2017. Dinoflagellate cysts and palynofacies across the Cretaceous–Paleogene boundary interval of the Vrancea Nappe (Eastern Carpathians, Romania). *Geological Quarterly* 61, 39–52.
- Țabără, D., Slimani, H., Mare, S., Chira, C.M., 2017. Integrated biostratigraphy and palaeoenvironmental interpretation of the Upper Cretaceous to Paleocene succession in the northern Moldavidian Domain (Eastern Carpathians, Romania). *Cretaceous Research* 77, 102–123.
- Tea-Yassi, J., Digbehi, Z.B., Yao, K.R., Glohi, B.V., 1999. Étude de quelques palynomorphes du Crétacé

- Supérieur du bassin offshore de Côte d'Ivoire: implications biostratigraphiques et paléoenvironnementales. *Journal of African Earth Sciences* 29, 783–798 (in French).
- Thompson, G.G., Yett, J.R., Green, K.E., 1984. Subsurface stratigraphy of the Ochoco Basin, Oregon. State of Oregon Department of Geology and Mineral Industries, Oil and Gas Investigation 8, 1–22.
- Thomsen, E., Heilmann-Clausen, C., 1985. The Danian-Selandian boundary at Svejstrup with remarks on the biostratigraphy of the boundary in western Denmark. *Geological Society of Denmark, Bulletin* 33, 341–362.
- Tocher, B.A., 1991. Late Cretaceous dinoflagellate cysts from the southern Kerguelen Plateau, Site 738. In: Barron, J., Anderson, J., Baldauf, J.G., Larsen, B. (Eds), *Proceedings of the Ocean Drilling Program, Scientific Results* 119, College Station, Texas, pp. 631–633.
- Torricelli, S., Amore, M.R., 2003. Dinoflagellate cysts and calcareous nannofossils from the upper Cretaceous Saraceno Formation (Calabria, Italy): Implications about the history of the Liguride Complex. *Rivista Italiana di Paleontologia e Stratigrafia* 109, 499–516.
- Toxwinius, B.B., 1986. Biostratigraphical zonation and correlation of five Late Cretaceous–Tertiary wells, offshore central West Greenland. *Grønlands Geologiske Undersøgelse, Rapport* 130, 36–43.
- Troncoso, A.A., Doubinger, J., 1980. Dinoquistes (Dinophyceae) del límite Cretácico-Terciario del Pozo El Ganso No 1 (Magallanes, Chile). *Actas del Segundo Congreso Argentino de Paleontología y Bioestratigrafía y Primer Congreso Latinoamericano de Paleontología* 2, 93–125 (in Spanish).
- Tucholke, B.E., Sibuet, J.-C., Klaus, A., Arnaboldi, M., Delius, H., Engström, A.V., Galbrun, B., Gardin, S., Hiscott, R.N., Karner, G.D., Ladner, B.C., Leckie, R.M., Chao-Shing Lee, Manatschal, G., Marsaglia, K.M., Pletsch, T.K., Pross, J., Robertson, A.H.F., Sawyer, D.S., Sawyer, D.E., Shillington, D., Shirai, M., Shryan, T., Stant, S.A., Takata, H., Urquhart, E., Wilson, C., Xixi Zhao, 2004. Site 1276. In: Nevill, H. Sherar, K. (Eds.), *Proceedings of the Ocean Drilling Program, Initial Reports* 210, College Station, Texas, pp. 1–358.
- Umeji, O.P., Edet, J.J., 2008. Palynostratigraphy and palaeoenvironments [sic] of the type area of Nsukka Formation of Anambra Basin, southeastern Nigeria. *Nigerian Association of Petroleum Explorationists, Bulletin* 20, 72–88.
- Umeji, O.P., Nwajide, C.S., 2007. Age control and designation of the standard stratotype of Nsukka Formation of Anambra Basin, southeastern Nigeria. *Journal of Mining and Geology* 43, 147–166.
- Van Pelt, R.S., Engelhardt, D.W., Christopher, R.A., Lucas-Clark, J., 2000. Establishing a hydrostratigraphic framework using palynology: An example from the Savannah River Site, South Carolina, U.S.A. In: Martin, R.A. (Ed.), *Environmental Micropaleontology, Topics in Geobiology* 15. Kluwer Academic/Plenum Publishers, New York, pp. 407–428.
- Van Stuijvenberg, J., 1980. Stratigraphie et structure de la Nappe du Gurnigel aux Voirons, Haute-Savoie. *Bulletin de la Société Fribourgeoise des Sciences Naturelles* 69, 80–96 (in French).
- Vasilyeva, O.N., 1990. Palynology and stratigraphy of Paleogene marine deposits in the southern Trans-Urals. *Zavaritsky Institute of Geology and Geochemistry, Ural Branch, Russian Academy of Sciences*, 57 pp. (in Russian).
- Vasilyeva, O.N., 2003. Dinocysts from deposits of the Talitsky Suites of the Trans-Urals. *Yearbook 2002, Zavaritsky Institute of Geology and Geochemistry, Ural Branch, Russian Academy of Sciences* 150, 20–30 (in Russian).
- Vasilyeva, O.N., 2007. Paleocene dinoflagellate assemblages from northern Turgay: Their significance for stratigraphy, correlation, and paleogeographic reconstructions. In: Gozhik, P.F. (Ed.), *Paleontological studies in Ukraine: History, present-day state and prospects. National Academy of Sciences of Ukraine, Institute of Geological Sciences, Paleontological Society, Kiev*, pp. 221–227, 532–533 (in Ukrainian).
- Vasilyeva, O.N., 2013. Paleogene dinocysts of the eastern Caspian Depression (Uspenskaya SP-1 borehole, Kazakhstan). *Lithosphere* 1, 102–127 (in Russian).
- Vasilyeva, O.N., 2017. Dinocysts of the Belogorodny Formation (Saratov Volga Region). *Yearbook 2016 (Stratigr., Paleontol.)*, Zavaritsky Inst. Geol. Geochem., Ural Branch, Russ. Acad. Sci. 164, 3–8 (in Russian).

- Vasilyeva, O.N., Levina, A.P., 2007. Organic-walled microphytoplankton from Upper Cretaceous and Paleogene sediments of the Kushmurun section in Turgay Depression (Kazakhstan). Moscow Society of Naturalists Bulletin, Geological Series 82, 40–56 (in Russian).
- Vasilyeva, O.N., Levina, A.P., 2010. Paleocene–early Eocene palynofloras of northern Kazakhstan. Paleontology and Stratigraphy News 14, 151–166 (in Russian).
- Vasilyeva, O.N., Musatov, V.A., 2010a. Paleogene biostratigraphy of the north Circum-Caspian region based on dinocysts and nannofossils from the Novouzensk borehole. Part 1: age substantiation and correlation of deposits. Stratigraphy and Geological Correlation 18, 83–104 (in Russian).
- Vasilyeva, O.N., Musatov, V.A., 2010b. Dinocysts and nannoplankton in the context of Ozinki (Obshchiy Syrt, northern Caspian Sea), preliminary results. Yearbook 2009 (Stratigraphy, Paleontology), Zavaritsky Institute of Geology and Geochemistry, Ural Branch, Russian Academy of Sciences 157, 17–25 (in Russian).
- Vasilyeva, O.N., Musatov, V.A., 2012. The Paleogene dinoflagellate cyst and nannoplankton biostratigraphy of the Caspian Depression. In: Elitok, Ö. (Ed.), Stratigraphic analysis of layered deposits. IntechOpen, Rijeka, Croatia, pp. 161–194.
- Vellekoop, J., Woelders, L., Sluijs, A., Miller, K.G., Speijer, R.P., 2019b. Phytoplankton community disruption caused by latest Cretaceous global warming. Biogeosciences 16, 1–19.
- Vellekoop, J., Smit, J., Van De Schootbrugge, B., Weijers, J.W.H., Galeotti, S., Sinninghe Damsté, J.S., Brinkhuis, H., 2015. Palynological evidence for prolonged cooling along the Tunisian continental shelf following the K–Pg boundary impact. Palaeogeography, Palaeoclimatology, Palaeoecology 426, 216–228.
- Vellekoop, J., Van Tilborgh, K.H., Van Knippenberg, P., Jagt, J.W.M., Stassen, P., Goolaerts, S., Speijer, R.P., 2019a. Type-Maastrichtian gastropod faunas show rapid ecosystem recovery following the Cretaceous–Paleogene boundary catastrophe. Palaeontology 63, 349–367.
- Vellekoop, J., Esmeray-Senlet, S., Miller, K.G., Browning, J. V, Sluijs, A., Van De Schootbrugge, B., Sinninghe Damsté, J.S., Brinkhuis, H., 2016. Evidence for Cretaceous–Paleogene boundary bolide “impact winter” conditions from New Jersey, USA. Geology 44, 619–622.
- Vellekoop, J., Holwerda, F., Prámparo, M.B., Willmott, V., Schouten, S., Cúneo, N.R., Scasso, R.A., Brinkhuis, H., 2017. Climate and sea-level changes across a shallow marine Cretaceous–Palaeogene boundary succession in Patagonia, Argentina. Palaeontology 60, 519–534.
- Vieira, M., Mahdi, S., 2019. New Paleocene species and biostratigraphic relevance of the genus *Spiniferites* across the North Sea and Norwegian Sea. Review of Palaeobotany and Palynology 262, 28–43.
- Vieira, M., Jolley, D. 2020. Stratigraphic and spatial distribution of palynomorphs in deep-water turbidites: A meta-data study from the UK central North Sea paleogene [sic]. Marine and Petroleum Geology 122, 104638.
- Vieira, M., Mahdi, S., Alderson, A., 2020a. New Selandian species of *Glaphyrocysta* and *Spinidinium* from offshore Northwest Europe. Review of Palaeobotany and Palynology 275, 104170.
- Vieira, M., Mahdi, S., Holmes, N., 2020b. High resolution biostratigraphic zonation for the UK central North Sea Paleocene. Marine and Petroleum Geology 117, 104400.
- Vieira, M., Mahdi, S., Osterloff, P., 2017. New early Paleocene (Danian) dinoflagellate cyst species from the Ormen Lange Field, Møre Basin, Norwegian Continental Shelf. Palynology 42, 180–198.
- Wade, J.A., Maclean, B.C., Williams, G.L., 1995. Mesozoic and Cenozoic stratigraphy, eastern Scotian Shelf: new interpretations. Canadian Journal of Earth Sciences 32, 1462–1473.
- Wetzel, O., 1933a. Die in organischer Substanz Erhaltenen Mikrofossilien des baltischen Kreide-Feuersteins mit einem sediment-petrographischen und stratigraphischen Anhang. Palaeontographica, Abteilung A 77, 141–187, pls. 1–2 (in German).
- Wetzel, O., 1933b. Die in organischer Substanz Erhaltenen Mikrofossilien des baltischen Kreide-Feuersteins mit einem sediment-petrographischen und stratigraphischen Anhang. Palaeontographica, Abteilung A 78, 1–110, pls. 1–4 (in German).
- Whitney, B.L., 1984. Dinoflagellate biostratigraphy of the Maestrichtian–Danian section in southern

- Maryland. In: Frederiksen, N.O., Krafft, K. (Eds). Cretaceous and Tertiary stratigraphy, paleontology, and structure, southwestern Maryland and northeastern Virginia. Field trip volume and guidebook (field trip held in Reston, Virginia, October 17). American Association of Stratigraphic Palynologists, Dallas, Texas, pp. 123–136.
- Williams, G.L., Bujak, J.P., 1977. Cenozoic palynostratigraphy of offshore eastern Canada. Contributions of stratigraphic palynology (with emphasis on North America). Volume 1. Cenozoic Palynology. Elsik, W.C. (Ed.), American Association of Stratigraphic Palynologists, Contributions Series 5A, pp. 14–47.
- Williams, G.L., Downie, C., 1966. V. Further dinoflagellate cysts from the London Clay. In: Davey, R.J., Downie, C., Sarjeant, W.A.S., Williams, G.L. (Eds.), Studies on Mesozoic and Cainozoic dinoflagellate cysts. Bulletin of the British Museum (Natural History), Geology, Supplement 3, pp. 215–236, pls. 24–26.
- Williams, G.L., Brinkhuis, H., Pearce, M.A., Fensome, R.A., Weegink, J.W., 2004. Southern Ocean and global dinoflagellate cyst events compared: index events for the Late Cretaceous–Neogene. In: Exon, N.F., Kennett, J.P., Malone, J.M. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results 189, College Station, Texas, pp. 1–98.
- Willumsen, P.S., 2011. Maastrichtian to Paleocene dinocysts from the Clarence Valley, South Island, New Zealand. *Alcheringa* 35, 199–240.
- Willumsen, P.S., 2012. Three new species of dinoflagellate cyst from Cretaceous–Paleogene (K–Pg) boundary sections at mid-Waipara River and Fairfield Quarry, South Island, New Zealand. *Palynology* 36, 48–62.
- Willumsen, P.S., Vajda, V., 2010. A new early Paleocene dinoflagellate cyst species, *Trithyrodinium partridgei*: its biostratigraphic significance and palaeoecology. *Alcheringa* 34, 523–538.
- Wilson, G.J., 1971. Observations on European Late Cretaceous dinoflagellate cysts. Part 1. Proceedings of the 2nd Planktonic Conference (Rome, 1970) 2, 1259–1275.
- Wilson, G.J., 1988. Paleocene and Eocene dinoflagellate cysts from Waipawa, Hawkes Bay, New Zealand. *New Zealand Geological Survey Paleontological Bulletin* 57, 1–96.
- Witts, J.D., Landman, N.H., Garb, M.P., Boas, C., Larina, E., Rovelli, R., Edwards, L.E., Sherrell, R.M., Cochran, J.K., 2018. A fossiliferous spherule-rich bed at the Cretaceous–Paleogene (K–Pg) boundary in Mississippi, USA: Implications for the K–Pg mass extinction event in the Mississippi Embayment and eastern Gulf Coastal Plain. *Cretaceous Research* 91, 147–167.
- Woelders, L., Vellekoop, J., Kroon, D., Smit, J., Casadío, S., Prámparo, M.B., Dinarès-Turell, J., Peterse, F., Sluijs, A., Lenaerts, J.T.M., Speijer, R.P., 2017. Latest Cretaceous climatic and environmental change in the South Atlantic region. *Paleoceanography* 32, 466–483.
- Xiaoqiao Wan, Tian Jiang, Yiyi Zhang, Dangpeng Xi, Guobiao Li, 2014. Palaeogene marine stratigraphy in China. *Lethaia* 47, 297–308.
- Yepes, O., 2001. Maastrichtian–Danian dinoflagellate cyst biostratigraphy and biogeography from two equatorial sections in Colombia and Venezuela. *Palynology* 25, 217–249.
- Young, M.D., Hannah, M.J., 2010. Dinoflagellate biostratigraphy of the vertebrate fossil-bearing Maungataniwha Sandstone, northwest Hawke’s Bay, New Zealand. *New Zealand Journal of Geology and Geophysics* 53, 81–87.
- Zaitzeff, J.B., Cross, A.T., 1970. The use of dinoflagellates and acritarchs for zonation and correlation of the Navarro Group (Maastrichtian) of Texas. *Geological Society of America, Special Papers* 127, 341–377.
- Zalinskaya, E.D., Naidin, D.P., 1985. Palynological characteristics of the upper Maastrichtian deposits of the Crimea. *Moscow Society of Naturalists Bulletin, Geological Series* 60, 80–87 (in Russian).
- Zaporozhets, N.I., Akhmetiev, M.A., Vitukhin, D.I., Sinelnikova, V.N., Fregatova, N.A., Soloviev, A. V., Khisamutdinova, A.I., 2015. Marine lower Paleogene of western Kamchatka (Tigil region) on dinocysts. *Moscow Society of Naturalists Bulletin, Geological Series* 90, 18–41 (in Russian).
- Zarei, E., Ghasemi-Nejad, E., 2015. Sequence stratigraphy of the Gurpi Formation (Campanian–Paleocene) in southwest of Zagros, Iran, based on palynomorphs and foraminifera. *Arabian Journal*

- of Geosciences 8, 4011–4023.
- Zarei, E., Ghasemi-Nejad, E., Dehbozorgi, A., 2017. Paleoclimate changes recorded in Gurpi Formation in south of Ilam based on playnomorphs and foraminifera. *Geosciences Scientific Quarterly Journal* 27, 245–252 (in Persian).
- Zastrozhnov, D., Gernigon, L., Gogin, I., Planke, S., Abdelmalak, M.M., Polteau, S., Faleide, J.I., Manton, B., Myklebust, R., 2020. Regional structure and polyphased Cretaceous-Paleocene rift and basin development of the mid-Norwegian volcanic passive margin. *Marine and Petroleum Geology* 115, 104269

Appendix 1.D. Geochemical and PGE concentrations data

Palynological Sample No.	UVic ID No.	Depth (m)	Amplitude (mV)	$\delta^{13}\text{C}_{\text{Carb}}$ ‰ VPDB	$\delta^{13}\text{C}_{\text{Carb}}$ ‰ VPDB Average	$\delta^{18}\text{O}$ ‰ VSMOW	$\delta^{18}\text{O}$ ‰ VSMOW Average	$\delta^{13}\text{C}_{\text{Org}}$ ‰ VPDB	$\delta^{13}\text{C}_{\text{Org}}$ ‰ VPDB Average
38	18-219	5.06	5144	-14.62	-14.53	18.66	18.62	-25.90	-26.01
			5661	-14.44		18.59		-26.12	
37	18-218	4.86	4614	-14.39	-14.39	18.25	18.25	-25.99	-26.01
								-26.03	
36	18-217	4.66	2103	-14.19	-14.36	10.69	10.57		-25.92
			2335	-14.53		10.45			
			785	-13.79		10.61			
			841	-13.93		10.58			
35	18-216	4.46	649	-16.04	-15.52	19.43	18.75	-26.30	-26.31
			633	-15.00		18.07		-26.31	
34	19-100	4.36	888	-15.24	-15.12	18.62	18.86	-25.74	-25.75
			978	-14.99		19.10		-25.75	
33	18-215	4.26	743	-16.63		19.30	18.90		-26.23
			673			18.50			
32	19-99	4.16	610	-15.36	-13.69	17.52	17.32		-26.41
			706	-12.02		17.12			
31	18-214	4.06	842	-17.52		16.17			-26.47
			1897	-18.24		16.92			
30	19-98	3.96	1079	-14.64		18.23		-25.58	
29	18-213	3.86	665	-13.97		14.00		-25.88	
	19-97	3.83	633	-13.67	-13.57	18.43	18.20		-27.44
			792	-13.48		17.97			
28	19-40	3.79	952	-14.95		17.31		-26.18	
	19-96	3.76	652			15.69	15.87	-26.25	-26.26
			815	-12.72		16.04		-26.27	
27	19-39	3.72	589	-15.21	-15.48	18.02	17.04		-25.56
			615	-15.07		16.81			
			655	-16.15		16.28			
	19-95	3.69	595			15.98	15.77	-25.73	-25.72
			831	-12.77		15.55		-25.70	
26	18-212	3.65	818			15.60		-25.69	
	19-94	3.62	542	-14.61	-14.67			-25.85	-25.97
			749	-14.72		15.12		-26.09	
25	19-38	3.58	626	-15.83		19.78		-25.86	-26.04
								-26.21	
	19-93	3.55	3993	-14.46		17.58		-27.38	-27.46
								-27.53	
24	19-37	3.51	558		-14.12	14.23	14.14		-26.77
			537	-14.00		13.11			
			875	-14.24		15.06			
	19-92	3.80	4146	-14.05	-13.91	17.58	17.62	-26.87	-26.98
			5906	-13.77		17.66		-27.09	
23	18-211	3.44	615	-15.03	-14.73	11.58	11.27		-25.50
			858	-14.43		10.96			
	19-91	3.40	619	-12.16					-26.03
			1700	-12.20		19.45			
22	19-36	3.36	556	-11.19	-11.50				-25.77
			944	-11.81		11.41			
21	18-184	3.31	809	-13.25		13.41		-25.70	-25.73
								-25.75	
20	19-35	3.27	733	-16.95	-15.64	17.61	14.23	-27.49	-27.33
			672	-17.62		10.98		-27.17	
			746	-12.33		14.10			
	19-90	3.22	2504	-14.50		17.89		-25.66	
19	19-34	3.17	592	-14.90	-13.85	17.29	16.16	-26.97	-26.82
			586	-14.46		17.42		-26.66	
			756	-12.19		13.76			
18	19-89	3.09	571	-15.17	-15.16				-27.46
			893	-15.15		13.64			
17	19-33	3.01	617	-16.14	-16.46	17.48	16.62		-27.52
			619	-16.78		15.76			
16	19-84	2.93	8453	-12.45	-12.76	17.38	17.49	-27.17	-27.15
			2439	-13.06		17.61		-27.10	
15	18-210	2.85	4552	-11.46		17.39		-27.43	

Grey values obtained under 1000 mV are unreliable given system blank of ~400 mV
Representative values for each sample in **bold**

Table 1. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values from the sampled Lynnwood interval.

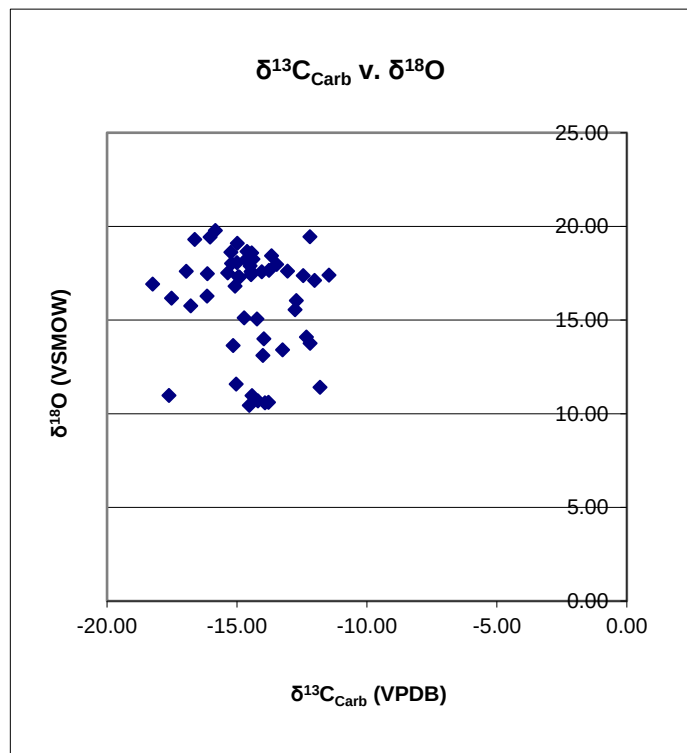


Table 2. Plotted $\delta^{13}\text{C}_{\text{Carb}}$ and $\delta^{18}\text{O}$ values from the sampled Lynnwood interval.

Palynological Sample No.	UVic ID No.	Depth (m)	Au (ppb)	Ir (ppb)	Pd (ppb)	Pt (ppb)	Rh (ppb)	Ru (ppb)
Detection Limit			0.4 (0.6)	0.01 (<0.025)	0.12 (0.2)	0.17 (0.19)	0.04 (0.05)	0.08 (0.08)
53	19-63	43.5	1.6	<0.025	0.93	0.86	<0.05	0.10
51	18-230	40.8	2.1	0.03	0.83	0.57	<0.05	<0.08
50	19-61	39.0	1.4	<0.025	0.38	0.35	<0.05	<0.08
49	18-229	37.4	<0.6	<0.025	0.21	0.25	<0.05	<0.08
42	18-183	11.0	1.3	<0.025	0.37	0.32	<0.05	<0.08
41	18-222	9.0	1.6	<0.025	0.92	0.54	<0.05	<0.08
40	18-221	7.0	1.2	<0.025	0.51	0.44	<0.05	<0.08
39	18-220	5.26	<0.6	<0.025	0.20	0.26	<0.05	<0.08
38	18-219	5.06	0.5	0.01	0.22	0.27	<0.04	0.11
36	18-217	4.66	<0.6	<0.025	0.22	0.22	<0.05	<0.08
35	18-216	4.46	0.6	<0.025	<0.20	0.23	<0.05	<0.08
33	18-215	4.26	<0.6	0.03	0.45	0.59	<0.05	<0.08
32	19-99	4.16	0.9	<0.025	0.22	0.26	<0.05	<0.08
30	19-98	3.96	1.4	0.02	0.48	0.41	<0.04	0.09
29	18-213	3.86	0.6	0.01	0.49	0.61	<0.04	0.10
N/A	19-96	3.76	1.1	0.02	0.74	1.06	0.06	0.18
26	18-212	3.65	0.7	0.01	0.29	0.42	<0.04	0.11
N/A	19-93	3.55	0.8	0.01	0.29	0.65	<0.04	0.11
23	18-211	3.44	0.80	0.02	0.33	0.89	0.04	0.16
22	19-36	3.36	<0.6	<0.025	0.22	0.23	<0.05	<0.08
21	18-184	3.31	270	<0.025	0.27	0.36	<0.05	<0.08
15	18-210	2.85	1.4	0.06	0.95	2.21	0.04	0.15

Table 3. Platinum Group element concentrations from the sampled Lynnwood interval. Initial sample suite values in bold. Second sample suite values in regular typeface.

Appendix 2.A. Total dinoflagellate cyst and *Cannosphaeropsis franciscana* Damassa, 1979 subspp. counts and concentrations | Table 1.

Sample		Sediment	Lycopodium spike			Dinoflagellate Cysts	C. f. franciscana		C. f. vacuoseptata		C. f. vesiculata		Hafniasphaera spp.		Spiniferites spp.	
Present Study	Institutional ID	Dry Weight (g)	Batch Number	Spores/Tablet	Spore Count	Total Count	Count	Cysts g ⁻¹	Count	Cysts g ⁻¹	Count	Cysts g ⁻¹	Count	Cysts g ⁻¹	Count	Cysts g ⁻¹
90	UVic 17-694	9.924	177745	18,584	367	454	1	5					3	15	39	199
89	UVic 18-236	4.276	2013001	27,560	1,474	416	1	4							12	53
88	UVic 18-176	4.400	177745	18,584	1,128 (1,603)	441 (627)	0 (2)	5				2	7	34	127	
87	UVic 18-235	4.171	2013001	27,560	461	426	4	57						35	502	
86	UVic 19-83	6.029	2013001	27,560	275	472	3	50				4	66	25	416	
85	UVic 17-693	9.833	177745	18,584	155 (334)	438 (944)	2 (4)	23				3	37	21	256	
84	UVic 18-177	4.439	177745	18,584	421	440	2	20				10	99	40	398	
83	UVic 19-82	6.044	2013001	27,560	431	443	4	42				19	201	51	540	
82	UVic 19-81	6.027	2013001	27,560	184 (302)	450 (739)	0 (1)	15				10	249	31	770	
81	UVic 19-80	6.033	2013001	27,560	3642	415	2	3				2	3	31	39	
80	UVic 19-79	6.029	2013001	27,560	2503	434	1	2				3	6	25	50	
79	UVic 19-78	6.016	177745	18,584	1009	436	1	3				5	15	38	116	
78	UVic 17-692	10.20	177745	18,584	265	433	2	14				8	55	17	117	
77	UVic 17-691	10.15	177745	18,584	145 (240)	433 (717)	3 (4)	31				2	25	31	391	
76	UVic 19-77	6.066	177745	18,584	126 (270)	455 (975)	6 (9)	102				5	122	50	1,216	
75	UVic 17-689	10.17	177745	18,584	76 (205)	435 (1,176)	3 (5)	45				3	72	28	673	
74	UVic 17-690	10.21	177745	18,584	67 (262)	433 (1,693)	6 (10)	69				1	27	19	516	
73	UVic 19-76	6.055	177745	18,584	58 (272)	450 (2,110)	2 (12)	135				11	582	43	2,275	
72	UVic 19-75	6.042	177745	18,584	52 (266)	445 (2,272)	3 (32)	370				12	710	44	2,603	
71	UVic 19-74	6.012	177745	18,584	57 (303)	431 (2,291)	4 (27)	275	(1)	10		6	325	30	1,627	
70	UVic 19-73	6.018	177745	18,584	73 (299)	443 (1,814)	7 (15)	155				10	423	29	1,227	
69	UVic 19-72	6.034	177745	18,584	100 (245)	463 (1,134)	3 (9)	113				5	154	55	1,694	
68	UVic 18-232	4.223	2013001	27,560	669	454	2	20				1	10	46	449	
67	UVic 19-71	6.026	177745	18,584	200 (269)	448 (603)	7 (8)	92						29	447	
66	UVic 19-70	6.043	177745	18,584	124 (225)	447 (811)	6 (13)	178				11	273	76	1,885	
65	UVic 19-69	6.066	177745	18,584	102 (258)	478 (1,209)	2 (7)	83				6	180	61	1,862	
64	UVic 19-68	6.050	177745	18,584	71 (233)	464 (1,523)	3 (9)	119				2	87	36	1,557	
63	UVic 19-67	6.043	177745	18,584	104 (244)	439 (1,030)	2 (7)	88				5	148	30	887	
62	UVic 18-178	4.420	177745	18,584	64 (436)	438 (2,984)	0 (9)	87	(5)	48		1	66	26	1,708	
61	UVic 19-66	6.068	177745	18,584	137 (1,183)	460 (3,972)	2 (32)	83	(2)	5		4	89	36	805	
60	UVic 18-179	4.429	177745	18,584	708	433	17	101	3	18	5	30	5	30	56	332
59	UVic 18-180	4.443	177745	18,584	569	452	6	44	2	15	5	37		23	169	
58	UVic 18-181	4.432	177745	18,584	327	434	15	192	1	13	9	115		12	154	
57	UVic 18-231	4.247	2013001	27,560	305	421	12	255	1	21	4	85		31	660	
55	UVic 19-64	6.077	2013001	27,560	10,638	341	1	0.4				3	1	36	15	
54	UVic 18-182	4.436	177745	18,584	868	430	16	77	7	34	2	10		9	43	
53	UVic 19-63	6.010	2013001	27,560	282	439	2	33				5	81	23	374	
52	UVic 19-62	6.037	2013001	27,560	938	426	13	63	2	10	6	29	2	10	19	92
51	UVic 18-230	4.241	2013001	27,560	212 (1,098)	464 (2,403)	0 (3)	18				7	215	21	644	
50	UVic 19-61	6.078	2013001	27,560	1,168	417	2	8	1	4	4	16		10	39	
49	UVic 18-229	4.272	2013001	27,560	996	434	11	71	5	32	4	26	1	7	20	130
48	UVic 18-228	4.245	2013001	27,560	3,316	107								2	4	
47	UVic 18-227	4.238	2013001	27,560	933	4								1	7	
46	UVic 18-226	4.275	2013001	27,560	2,362	88								10	27	
45	UVic 18-225	4.175	2013001	27,560	2,145	210								23	71	
44	UVic 18-224	4.247	2013001	27,560	2,647	235								32	78	
43	UVic 18-223	4.265	2013001	27,560	905	426								65	464	
42	UVic 18-183	4.379	177745	18,584	172	429								25	618	
41	UVic 18-222	4.259	2013001	27,560	402	446						1	16	74	1,191	
40	UVic 18-221	4.270	2013001	27,560	520	439								104	1,291	
39	UVic 18-220	4.230	2013001	27,560	2,405	454								161	436	
38	UVic 18-219	4.162	2013001	27,560	1,829	435								186	673	
37	UVic 18-218	4.164	2013001	27,560	2,263	433								190	556	
36	UVic 18-217	4.079	2013001	27,560	1,653	457						1	4	226	926	
35	UVic 18-216	4.134	2013001	27,560	1,438	448								135	626	
34	UVic 19-100	6.022	2013001	27,560	938	422								156	761	
33	UVic 18-215	4.096	2013001	27,560	1,788	435								175	654	
32	UVic 19-39	6.018	2013001	27,560	1,813	461								204	515	
31	UVic 18-214	4.137	2013001	27,560	4,351	432						7	11	265	424	
30	UVic 19-98	6.01	2013001	27,560	2,351	427						1	2	197	384	
29	UVic 18-213	4.223	2013001	27,560	5,430	427						11	12	254	287	
28	UVic 19-40	8.085	2013001	27,560	7,469	427						2	1	271	124	
27	UVic 19-39	8.082	2013001	27,560	9,027	435						2	1	274	103	
26	UVic 18-212	4.273	2013001	27,560	6,890	433						7	7	218	204	
25	UVic 19-38	8.079	2013001	27,560	7,049	427								256	124	
24	UVic 19-37	8.098	2013001	27,560	7,229	432						2	1	291	137	
23	UVic 18-211	4.176	2013001	27,560	7,572	437						1	1	267	225	
22	UVic 19-36	8.058	2013001	27,560	6,017	429						3	3	286	163	
21	UVic 18-184	4.379	177745	18,584	24 (524)	427 (9,323)	0 (5)	40				0 (1)	8	13	2,299	
20	UVic 19-35	8.054	2013001	27,560	10,268	427								245	81	
19	UVic 19-34	8.049	2013001	27,560	16,661	306						1	0.2	178	37	
18	UVic 19-89	6.023	2013001	27,560	6,630	420								205	126	
17	UVic 19-33	8.071	2013001	27,560	6,814	85								48	24	
16	UVic 19-84	5.767	2013001	27,560	11,280	107								52	22	
15	UVic 18-210	4.170	2013001	27,560	1,782	4								3	11	
14	UVic 18-209	4.194	2013001	27,560	4,766	13								7	10	
13	UVic 18-208	4.228	2013001	27,560	3,637	9								5	9	
10	UVic 18-205	4.172	2013001	27,560	1,750	4								2	8	
4	UVic 18-199	4.122	2013001	27,560	3,404	8								7	14	

Grey fill = float samples; data excluded from calculations

Bold typeface = recorded count values

Regular typeface = extrapolated values

Base values relative to total dinoflagellate cyst counts > 300 specimens

Bracketed values relative to *Lycopodium* spore counts ≥ 1% of tablet

Appendix 2.B. Measurements of *Cannosphaeropsis franciscana* Damassa, 1979 subspp.

Table 1. Specimens of *Cannosphaeropsis franciscana* subsp. *franciscana* (autonym)

Sample	Specimen ID	Citation and Figures	Extrapolated measurements (μm)								
			L ₁	W ₁	L ₂	W ₂	T ₁	T ₂	T ₃		
PL 4764	UCLA 58135*	Damassa (1979, p. 204, Pl. V, 1, 2, 6); Pl. I, 1–3 (this study)	61.7	49.2	146.9	111.5	–	2.1	–		
PL 4764	UCLA 58139	Damassa (1979, Pl. V, 7, 10)	50.6	40.2	109.4	95.2	–	2.8	1.9		
PL 4764	UCLA 58140	Damassa (1979, Pl. V, 11)	51.9	–	115.6	–	–	3	2.7		
PL 4764	UCLA 58141	Damassa (1979, Pl. IV, 7)	–	41.4	–	90.4	–	–	2.5		
		Drugg (1967, Pl. IV, 16); Damassa (1979, Pl. V, 8, 9); Pl. II, 9 (this study)	67	58	126	95	–	4	3		
Sample		Slide	EF Coordinates	Figures	Measurements (μm)						
Number	UVic ID				L ₁	W ₁	L ₂	W ₂	T ₁	T ₂	T ₃
21	18-184	A	D32/3		52.5	43.6	94.9	83.9	1.2	1.8	5.1
21	18-184	B	R34/0	Pl. II, 1, 2	54.9	40.9	113.5	90.8	1	1.8	3.2
21	18-184	F	R25/0	Pl. II, 4–6	61.7	–	116.8	–	1	2.5	2
21	18-184	F	T40/2		64.3	–	144.8	–	1.5	3	2.3
49	18-229	A	K34/3		58.8	49.5	100.7	67.3	0.8	2.4	2.8
49	18-229	B	U36/0		49.5	38.7	97.1	79.1	1	2	1.8
49	18-229	C	K40/1		72.8	51.3	103.6	86.6	0.8	2.4	1.8
51	18-230	B	E41/0		55.1	33.6	125.1	67.3	1.4	2.8	2.2
51	18-230	C	M31/0		60.4	42.4	115.5	63	0.8	2.8	2
53	19-63	A	U29/3		47.8	33.2	85.3	70.5	0.8	2.2	1.6
54	18-182	A	E32/2	Pl. II, 3	58.8	47	88.8	93	1	2.4	1.8
54	18-182	A	G45/0		51.3	38.7	115.9	78.2	1	2.4	2
54	18-182	A	P46/1		63	48	136.6	92	1.5	2.8	2.2
54	18-182	A	U44/4		46.4	36.3	108.4	65.3	0.8	1.8	–
54	18-182	A	N27/1		51.1	41.4	115.1	81.3	1.4	2.2	2
54	18-182	A	M28/0		57	42.2	121.2	71.8	1	2	2
54	18-182	A	L38/1		53.7	34.5	102.4	67.1	0.8	1.4	3.4
54	18-182	B	R36/4		48.6	37.1	85.3	68.3	0.8	1.8	2.4
54	18-182	B	L30/1		43.2	33.4	97.7	52.9	0.8	3.4	1.6
54	18-182	B	K47/3		63.4	40.1	121.8	83.9	1	2.4	2.4
54	18-182	B	K27/0		39.3	32.2	70.1	61.2	0.8	1.2	0.8
54	18-182	B	F40/1		68.1	47.6	134	92.4	1.4	3.4	2
54	18-182	B	O42/3		–	47.2	–	101.6	1.2	2.4	1.8
57	18-231	A	K36/1		48.4	42.2	89.8	67.3	1	2.2	2.2
57	18-231	A	P33/3		54.9	38.1	111.3	78.6	0.8	5	2.8
57	18-231	A	E27/2		48	39.7	102.4	66.7	0.8	3.6	2.6
57	18-231	A	F32/0		40.5	32.6	64.5	60	–	1.4	1.8
57	18-231	B	Y36/0		52.3	40.1	88.8	66.7	1.5	3.4	2.2
57	18-231	B	V43/4		–	41.5	–	63	0.8	2.2	2
58	18-181	C	P50/0		47	44.6	87.4	76.8	1	3	1.6
58	18-181	C	E39/3		47.6	34.5	75.2	67.5	1	1.8	2
58	18-181	C	G42/4		46.6	39.3	85.9	78.4	1	3	2.4
58	18-181	C	L50/0		55.5	41.6	93	84.7	1.2	2.4	2.2
58	18-181	C	M51/1		–	53.5	–	72	0.8	3	1.8
58	18-181	C	N34/0	Pl. II, 8	56.4	52.9	103.4	89.8	0.8	3.2	3.6
58	18-181	C	R48/3		57.8	44	108.2	68.7	0.8	2.4	2.4
58	18-181	C	V45/2		55.1	44.2	103.2	67.9	1	2.2	1.8
58	18-181	C	V48/4		52.3	43.8	91.2	81.9	0.8	1.4	1.8
58	18-181	C	W43/3	Pl. II, 7	49.3	42.4	100.1	80.1	1	2.2	2
59	18-180	B	G34/3		53.1	41.8	85	88	1	2.2	2.2
59	18-180	B	J31/2		46.6	41.4	89.8	76.8	1.2	2.8	2
60	18-179	B	Q34/4		56.8	40.9	122.6	–	1	1.8	2
60	18-179	B	S32/1		49.7	33.9	98.7	62.2	0.8	2	2.4
65	19-69	B	T28/2		66.9	53.9	97.3	88.2	0.8	2.6	2
68	18-232	A	T36/1	Pl. I, 6, 7	59.6	48	110.5	95.7	1.2	3	2.6
74	17-690	C	B38/3		56.1	43.1	110.9	91.4	1.1	3.8	3.6

Table 1. Continued.

74	17-690	C	D40/0		56.6	46	97.3	66.7	1.2	3.2	4.5
74	17-690	C	D43/4		60.2	41.1	92.8	82.7	1.2	2.4	2.4
74	17-690	C	M50/0		49.3	38.9	91	75.6	1.3	2.8	2.2
74	17-690	C	N34/4		50.1	43.6	107.4	67.1	1.4	2.6	2.8
74	17-690	C	P32/3		65.9	47.2	104.6	85.1	1	4.5	4.7
74	17-690	D	D39/4		41.8	38.5	75.2	77.6	1	2.2	1.4
74	17-690	D	L50/2		56.8	41.1	85.9	65.7	1.2	3	1.8
74	17-690	D	R48/3		59.8	53.5	112.7	101.8	1.3	3.6	3
78	17-692	D	L29/2	Pl. I, 4, 5; Pl. III, 8	58.4	44.4	119.2	89.2	1	2.8	3.2
78	17-692	D	Q38/1		59.4	48.9	141.1	100.5	1.2	2.8	3.2
86	19-83	A	O36/4	Pl. III, 2–4	51.1	52.7	82.1	110.5	1.1	1.4	1.6
86	19-83	A	L41/3	Pl. III, 1	53.7	43.2	86.8	79.1	1.1	2	1.8
86	19-83	B	V39/1	Pl. III, 5–7	49.5	44.6	93.4	74.2	0.8	1.6	1.2
89	18-236	C	L35/0		52.5	36.7	108	62.8	1	3.4	2
90	17-694	B	G37/0	Pl. I, 8–10; Pl. III, 9, 10	64.5	51.5	133	121	1.4	3.5	3.2
90	17-694	B	O43/0		51.3	45	115.7	78.9	1.2	2.8	2.2
90	17-694	D	T33/0		57	44	121.4	118.2	1	4.7	3
		Stub	Specimen ID	Figures							
58	19-42	C	C.C.01	Pl. VII, 6–8	47.5	37.9	106.8	69.9	–	2.7	2.8
60	19-41	1	1.1.01		53.7	40.2	111.6	80.8	–	2.3	1.8
60	19-41	1	1.1.02		52.3	–	112.3	–	–	2.9	3
60	19-41	1	1.1.03		–	41.9	–	73.8	1.4	2.8	2.7
60	19-41	1	1.1.04	Pl. VIII, 1–3	66.8	44	114.3	96.8	–	2.7	2
60	19-41	Pin Stub	P.1.01	Pl. VI, 1–3, 10	54.4	43.3	88.8	77.5	–	2.2	1.9
62	19-31	A	A.C.01	Pl. VIII, 4–6, 8	64	49.8	118.6	84.7	1	–	3.2
62	19-31	A	A.C.02	Pl. VII, 3	52.9	43.1	103.6	77.3	–	2	2.4
62	19-31	A	A.C.03	Pl. VI, 4–9; Pl. VII, 9	53.4	42	103.2	82.1	–	2.3	1.8
62	19-31	A	A.C.04	Pl. VII, 1, 2, 4, 5	58.7	46	127.6	89.9	–	2.9	2.7
62	19-31	X	X.1.01	Pl. VIII, 7	–	–	–	–	1.5	–	–

Measurements from specimens of the original type series not provided by Damassa (1979) are derived from their respective photomicrograph magnifications given therein as well as from the dimensions provided by Drugg (1967).

Table 2. Specimens of *Cannosphaeropsis franciscana* subsp. *vacuoseptata* subsp. nov.

Sample		Slide	EF Coordinates	Figures	Measurements (μm)						
Number	UVic ID				L ₁	W ₁	L ₂	W ₂	T ₁	T ₂	T ₃
49	18-229	C	P38/4		52.3	39.7	101.1	81.1	1.6	2.6	1.8
54	18-182	A	P48/2		55.3	41.4	110.3	53.5	2.6	1.8	1.6
54	18-182	A	F36/0		53.3	43.4	109.5	82.7	2.4	2.4	1.6
54	18-182*	B	G33/3	Pl. 3.4, figs. 1–3	62.4	44.1	91.4	80.5	2.6	2.2	2.4
57	18-231	A	Q40/0		49.1	35.3	70	53.7	2.2	1.8	–
57	18-231	B	Y31/2		47.8	39.3	71.4	52.5	1.6	2.2	2
57	18-231	B	D37/3	Pl. 3.4, fig. 8	54.9	44.4	88.4	75.4	2.6	3.5	1.4
57	18-231	B	L43/1	Pl. 2.4, figs. 9, 10	49.9	40.9	81.9	62	1.8	3	1.6
58	18-181	A	T38/4		55.7	43.2	67.5	58.6	1.5	1.8	1.4
58	18-181	C	O27/3		42.2	–	75	–	2.8	2.6	1.4
58	18-181	C	D34/1		53.7	45.8	–	73.2	2.4	3	2.4
58	18-181	C	E34/3		46.4	36.5	73	53.7	2.8	2.4	1.4
58	18-181	C	G36/3		51.4	38.7	72.2	–	2.2	1.6	1.4
59	18-180	A	E26/1		64.9	51.7	99.3	76.8	2.8	2.8	2.8
59	18-180	B	F30/0		57.1	–	85.7	–	2.4	2.2	1
60	18-179	A	K41/0	Pl. 2.4, figs. 4–7	54.1	45.2	105.4	83.5	–	3.2	2.2
60	18-179	B	K29/0		58.6	41.8	132.2	85.5	2.2	2.4	2.4
60	19-41	B	M36/2		–	–	86.1	–	1.8	1.8	1.2
62	18-178	B	K34/1		60.6	46	113.7	84.7	2.6	3.2	2.6
		Stub	Specimen ID	Figures							
60	19-41	B	B.S.03	Pl. 3.10, fig. 3	53.3	43.4	106.2	76.4	–	2.3	2.5
60	19-41	B	B.S.04	Pl. 3.9, figs. 4, 5	54	–	112.4	–	–	2.1	1.9
60	19-41	B	B.S.05	Pl. 3.9, figs. 6–10	52.5	42.7	126.7	73.2	1.6	2.1	2.9
60	19-41	B	B.T.01		54.9	43.9	98.9	80.2	–	2.8	2
60	19-41	B	B.T.04	Pl. 3.9, figs. 1–3	54.6	41.2	96.8	81.8	–	2.4	2.4
62	18-178	A	A.S.01	Pl. 3.10, figs. 5–8; Pl. 3.11, figs. 1–3	54.3	46.8	91.8	74.9	2.6	2.2	2.8
62	18-178	A	A.S.02	Pl. 3.10, figs. 1, 2, 4	58.5	42.9	101.7	75.8	–	2.2	2.3

Table 3. Specimens of *Cannosphaeropsis franciscana* subsp. *vesiculata* subsp. nov.

Sample		Slide	EF Coordinates	Figures	Measurements (μm)						
Number	UVic ID				L ₁	W ₁	L ₂	W ₂	T ₁	T ₂	T ₃
54	18-182	A	N41/0		61.6	45.2	97.5	97.3	3.4	3.2	3
54	18-182	B	P26/3		–	46.4	–	83.9	3.2	2.8	1.8
57	18-231	A	E45/1		53.7	47.6	95.7	76	3.2	2.8	1.6
57	18-231	A	T40/4		64.3	57.6	116.8	81.5	3.4	4.1	2.2
57	18-231	B	Y36/0		54.7	51.5	78.4	89.2	4.3	3.4	1.8
58	18-181	C	H28/0		63.4	55.5	91.4	82.9	4.1	2	1
58	18-181	C	K51/4		58.6	52.9	–	61.2	3.2	1.6	1.4
58	18-181	C	N38/0		63.4	53.1	92.6	75.2	4.1	1.8	1.4
58	18-181	C	N38/3	Pl. 35, figs. 4, 5	67.1	55.7	101.4	94.9	4.2	2.8	3
58	18-181*	C	R37/3	Pl. 3.5, figs. 1–3	54.9	52.7	94.9	94.9	4.1	3.4	3
58	18-181	C	Q42/4		–	55.5	–	89	3.2	3.4	2.6
58	19-42	A	X43/1		52.1	42.2	96.5	76	4.1	3.2	2.2
58	19-42	A	N35/1		65.7	45.6	101.4	72	3.4	3	3.2
58	19-42	A	W36/1		60.4	45.4	97.5	77.8	3.2	2.8	2.8
59	18-180	B	O39/2		66.7	51.3	–	103.8	3.9	2.4	1.8
60	18-179	A	O46/4		–	41.8	–	70.3	3.2	1.8	2.2
60	18-179	A	J37/0	Pl. 3.5, fig. 6	52.7	44	99.1	87.8	3.4	2	1.6
60	19-41	A	V35/2	Pl. 3.5, figs. 7–9	–	–	–	–	–	3	2.2
		Stub	Specimen ID	Figures							
58	18-181	C	C.T.02	Pl. 3.12, figs. 1, 2	–	–	–	–	3.2	–	–
60	19-41	B	B.S.01	Pl. 3.12, figs. 6–8	53.8	52.6	96.1	90	–	2.4	1.9
60	19-41	B	B.S.02	Pl. 3.12, figs. 4, 5	57.8	53	103.2	97.2	–	2	1.9
60	19-41	B	B.T.02		51.2	41.3	105.6	82.8	–	2.3	1.8
60	19-41	B	B.T.03	Pl. 3.12, fig. 3	52.7	–	116.7	–	–	3.2	2.1
60	19-41	Y	Y.1.01	Pl. 3.11, figs. 4, 5	49.9	–	85.9	–	–	2.4	–
60	19-41	Y	Y.1.02	Pl. 3.11, figs. 6, 7	60.8	–	106.8	–	2.7	2.3	2.5

* = holotypes

References

- Damassa, S.P., 1979. Danian dinoflagellates from the Franciscan Complex, Mendocino County, California. *Palynology* 3, 191–207.
- Drugg, W.S., 1967. *Palynology of the upper Moreno Formation (Late Cretaceous–Paleocene) Escarpado Canyon, California*. Palaeontogr. Abteilung B 120, 1–71, 9 pls.

Appendix 2.C. Global distribution of *Cannosphaeropsis* and *Hafniasphaera* species

We present a review of the reported geographic and chronostratigraphic distributions of the seven definitive species belonging to the genus *Cannosphaeropsis* following Fensome et al. (2019) and all reports of taxa assigned to *Hafniasphaera* accompanied by photomicrographs. Records prior to 2004 were retrieved with the assistance of the PALYNODATA online database (Palynodata Inc. and White, 2008). A record is herein defined as an original reported occurrence of a taxon as it relates to a given geological formation or regional rock package within the scope of a published study. If an occurrence is described as reworked, it is afforded a separate entry as a report independent of the allochthonous range within a given study. Conference abstracts and summative publications such as catalogues and indices have not been included. Age placements have been noted to stage level as stated in the original work or where otherwise deducible.

Nominal species reports accompanied by photomicrographs have their publication dates in bold whereas solely nominal reports have their publication dates in regular typeface (e.g. Deflandre, 1935, **1937**). A strikethrough date denotes a record not accepted due to misidentification. Symbolology is as follows: An asterisk (*) preceding the date denotes the original publication designating the holotype of the presently accepted species. A question mark (?) preceding the region or country denotes uncertainty of record provenance; a question mark preceding the date denotes uncertainty pertaining to a species assignment; a question mark preceding an age assignment denotes uncertainty when a precise chronostratigraphic position or range of an occurrence was not indicated within a study encompassing a broader time interval. A superscript letter R preceding the date (^R) denotes a report regarded by the authorship of the given publication to have been reworked.

Systematic Paleontology

Division: DINOFLAGELLATA (Bütschli, 1885) Fensome et al., 1993

Subdivision: DINOKARYOTA Fensome et al., 1993

Class: DINOPHYCEAE Pascher, 1914

Subclass: PERIDINIPHYCIDAE Fensome et al., 1993

Order: GONYAULACALES Taylor, 1980

Suborder: GONYAULACINEAE (autonym)

Family: GONYAULACACEAE Lindemann, 1928

Subfamily: GONYAULACOIDEAE (autonym)

Genus: ***Cannosphaeropsis*** (Wetzel, 1933) Marheinecke, 1992

Cannosphaeropsis australis Riding & Helby, 2001

- 1962** *Cannosphaeropsis* sp. cf. *C. utinensis* (Wetzel) Cookson & Eisenack, p. 493; pl. 4, fig. 4 [Early Cretaceous (?Apitan–Albian), western Australia].
- *2001** *Cannosphaeropsis australis* Riding & Helby, p. 227, 229; figs. 1A–1I, appendix 2 [Early Cretaceous (late Apitan–early Albian), offshore western Australia].
- 2004** *Cannosphaeropsis australis* (Riding & Helby) Helby et al., fig. 1 [Early Cretaceous (early Albian), offshore western Australia].
- 2006** *Cannosphaeropsis australis* (Riding & Helby) Backhouse, p. 52; pl. 2, fig. 8, appendix 1 [Early Cretaceous (early Albian), offshore western Australia].

Remarks: The specimen figured by Backhouse (2006, pl. 2, fig. 8) appears to be comprised of only the trabecular ectophragm. A free floating autophragm, as has been described for this species (Riding and Helby, 2001), would certainly lend to the disassociation of inner and outer bodies.

Cannosphaeropsis franciscana Damassa, 1979

- 1967** *Cannosphaeropsis filifera* (Cookson & Eisenack, 1958) Cookson & Eisenack, 1960 | Drugg, p. 25; pl. 4, fig. 16 [early Paleocene (Danian), California].
- *1979** *Cannosphaeropsis franciscana* Damassa, p. 204, 205; pl. 4, fig. 9, pl. 5, figs. 1–11 [early Paleocene (Danian), California].
- 2011** *Cannosphaeropsis francisca* [sic] (Damassa) Slimani et al., table 1, appendix A [Late Cretaceous (late Maastrichtian)–early Paleocene (late Danian), Belgium].
- 2021** *Cannosphaeropsis franciscana* (Damassa) McLachlan & Pospelova, pl. 5, fig. M, appendices A, B [Late Cretaceous (latest Maastrichtian)–early Paleocene (earliest Selandian), Vancouver Island, British Columbia].
- 2021** *Cannosphaeropsis franciscana* (Damassa) this study, figs 2–6, Pl. 3.1, figs. 1–10 (figs. 1–3 *redux* Damassa, 1979), Pl. 3.2, figs. 1–9 (fig. 9 *redux* Damassa, 1979), Pl. 3.3, figs. 1–10, Pl. IV, figs. 1–10, Pl. 3.5, figs. 1–9, Pl. 3.6, figs. 1–10, Pl. 3.7, figs. 1–9, Pl. 3.8, figs. 1–8; Pl. 3.9, figs. 1–10, Pl. 3.10, figs. 1–8, Pl. 3.11, figs. 1–7, Pl. 3.12, figs. 1–8, appendices A–C [Late Cretaceous (latest Maastrichtian)–early Paleocene (earliest Selandian), Vancouver Island, British Columbia].

Cannosphaeropsis hughesii Harding, 1990

- *1990** *Cannosphaeropsis hughesii* Harding, p. 24, 25; pl. 6, figs. 9–16, text-fig. 18, tables 3, 4, 6, appendix 1 [Early Cretaceous (late Hauterivian), northern Germany].

- 1995** *Cannosphaeropsis hughesii* (Harding) Heilmann-Clausen & Thomsen, p. 266, 292; pl. 8, figs. 9, 10, folding fig. 4 [Early Cretaceous (early Barremian), northern Germany].

Remarks: The report of Heilmann-Clausen and Thomsen (1995) represents a probable occurrence albeit based on a single damaged specimen.

Cannosphaeropsis passio de Verteuil & Norris, 1996

- ?1943 *Cannosphaeropsis utinensis* (Wetzel) de Wit, p. 387; fig. 15 [Miocene (?Serravallian), Belgium].
- 1975** *Nematosphaeropsis* sp. A Williams & Brideaux, p. 27, 29; pl. 14, fig. 8, pl. 17, fig. 7, folding fig. 7, 15b, appendix [late Miocene (?Tortonian), offshore eastern Canada].
- 1977 *Nematosphaeropsis* sp. A (Williams & Brideaux) Williams & Bujak, p. 25, 26 [late Miocene (?Tortonian), offshore eastern Canada].
- 1979 *Nematosphaeropsis* sp. A (Williams & Brideaux) Barss et al., p. 67; appendix [middle Miocene (?Serravallian), offshore eastern Canada].
- 1985** *Cannosphaeropsis utinensis* (Wetzel) Brown & Downie, fig. 1, pl. 4, fig. 11 [early Eocene (?early Ypresian)–late Miocene (Tortonian), offshore Ireland].
- 1989** *Cannosphaeropsis utinensis* (Wetzel) Manum et al., table 2; pl. 4, figs. 5, 6, [early–middle Miocene (?lower Burdigalian–Serravallian), offshore Norway].
- 1992** *Cannosphaeropsis utinensis* (Wetzel) Engel, p. 32, 131; fig. 12, pl. 6, figs. 5, 6, appendices 2, 3 [middle–late Miocene (?Langhian –?early Tortonian), North Atlantic].
- 1992** *Cannosphaeropsis utinensis* (Wetzel) *sensu* Brown & Downie | Head & Wrenn, p. 4, 5; pl. 9, figs. 1–10, pl. 10, figs. 1, 2 [middle Miocene (?Serravallian), Virginia].
- 1992** *Cannosphaeropsis utinensis* (Wetzel) *sensu* Brown & Downie | Powell, p. 220, 221; fig. 4.10, pl. 4.11, fig. 14, appendix B [late Miocene (late Tortonian), North Sea].
- 1993** *Cannosphaeropsis utinensis* (Wetzel) Lund et al., p. 30, 33; pl. fig. 5, text-fig. 2 [middle Miocene (Serravallian), northern Germany].
- ?1994 *Cannosphaeropsis* cf. *utinensis* (Wetzel) Mountain et al., p. 29, 85, 86, 157, 226, 227, 279, 324, 325; ch. 6, table 6, ch. 7, table 4 [late middle Miocene (Serravalian), offshore New Jersey].
- 1996 *Cannosphaeropsis passio* (de Verteuil & Norris) de Verteuil, p. 439, 443; fig. 1, tables 1–6 [middle Miocene (Serravallian), offshore New Jersey].
- *1996** *Cannosphaeropsis passio* de Verteuil & Norris, p. 12–14, 32, 34, 48, 55, 58, 130, 134, 136; pl. 2, figs. 2, 3, pl. 7, figs. 1–8, pl. 8, figs. 1–6, pl. 17, figs. 1, 3, 4, 7, text-fig. 3, 22, tables 1, 2, 8, appendix 2 [middle Miocene (late Serravallian), Maryland, Virginia].

- ?1996 *Cannosphaeropsis utinensis* (Wetzel) Gradstein & Bäckström, p. 22; fig. 2 [late early–early late Miocene (Serravallian–?Tortonian), offshore Norway].
- 1996** *Cannosphaeropsis* cf. *utinensis* (Wetzel) *sensu* Brown & Downie | McCarthy & Mudie, p. 255; pl. 2, fig. 10, tables 1, 2 [early Miocene, offshore Portugal].
- 1997 *Cannosphaeropsis passio* (de Verteuil & Norris) de Verteuil, p. 132, 139, 141; fig. 5, table 1 [middle Miocene (late Serravallian), New Jersey].
- 2000** *Cannosphaeropsis passio* (de Verteuil & Norris) Louwye et al., p. 387; fig. 5, fig. 7e, 7f [middle Miocene (late Serravallian), North Sea].
- 2001** *Cannosphaeropsis passio* (de Verteuil & Norris) Strauss et al., p. 400, 418, 420, 421, 427; pl. 3, figs. 1, 2 [middle Miocene (late Serravallian), northern Germany].
- 2002 *Cannosphaeropsis passio* (de Verteuil & Norris) Louwye, p. 58 [middle Miocene (late Serravallian), Belgium].
- 2003** *Cannosphaeropsis passio* (de Verteuil & Norris) Piasecki, p. 1086; pl. 4, fig. 10 [middle Miocene (latest Serravallian), offshore West Greenland].
- 2004** *Cannosphaeropsis passio* (de Verteuil & Norris) Munsterman & Brinkhuis, p. 275, 282; figs. 19, 22 [middle Miocene (late Serravallian), North Sea].
- 2005 *Cannosphaeropsis passio* (de Verteuil & Norris) Louwye, p. 449, 450; fig. 4 [middle Miocene (middle Serravallian), Belgium].
- 2005** *Cannosphaeropsis passio* (de Verteuil & Norris) Schiøler, fig. 2, pl. 1, fig. 10 [early Oligocene (middle Rupelian)–early Miocene (late Burdigalian), North Sea].
- 2005 *Cannosphaeropsis passio* (de Verteuil & Norris) Vandenberghe et al., p. 20, 22; fig. 8, 9, table 2 [middle Miocene (late Serravallian), northern Germany].
- 2007** *Cannosphaeropsis passio* (de Verteuil & Norris) Köthe, p. 294, 295, 303; pl. 2, fig. 2, table 1, 2 [middle Miocene (late Langhian–early Serravallian), North Sea].
- 2007 *Cannosphaeropsis passio* (de Verteuil & Norris) Köthe & Piesker, p. 12 [middle Miocene (late Serravallian), northern Germany].
- 2007 *Cannosphaeropsis passio* (de Verteuil & Norris) Schiøler et al., p. 68; fig. 5c [middle Miocene (late Serravallian), North Sea].
- 2008 *Cannosphaeropsis passio* (de Verteuil & Norris) Louwye & Laga, p. 86 [middle Miocene (middle–late Serravallian), Belgium].
- 2008a *Cannosphaeropsis passio* (de Verteuil & Norris) Louwye et al., p. 332, 334, 336; figs. 4a, 7, 9 [middle Miocene (middle–late Serravallian), offshore Ireland].
- 2008b *Cannosphaeropsis passio* (de Verteuil & Norris) Louwye et al., p. 132; text-fig. 3 [middle Miocene (late Serravallian), offshore Ireland].

- 2010** *Cannosphaeropsis passio* (de Verteuil & Norris) Dybkjær & Piasecki, p. 18; fig. 6, pl. 2, fig. d [middle Miocene (middle Serravallian), Denmark, North Sea].
- 2010 *Cannosphaeropsis passio* (de Verteuil & Norris) Rasmussen et al., fig. 6 [middle Miocene (middle Serravallian), Denmark].
- 2012 *Cannosphaeropsis passio* (de Verteuil & Norris) Anthonissen, p. 292; figs. 3, 7, appendix 1 [late Miocene (earliest Tortonian), offshore Norway].
- 2012 *Cannosphaeropsis passio* (de Verteuil & Norris) González et al., p. 10 [middle Miocene (late Serravallian), Maryland] .
- ?2014 *Cannosphaeropsis passio* (de Verteuil & Norris) Beiranvand et al., p. 251; table 2, appendix A [early Paleocene (early Danian), Iran].
- 2014** *Cannosphaeropsis passio* (de Verteuil & Norris) Quaijtaal et al., p. 151; fig. 5, pl. 2, figs 7, 8, table 1, supp. fig. 2, supp. table 1 [middle Miocene (middle Serravallian), offshore Ireland].
- 2016** *Cannosphaeropsis passio* (de Verteuil & Norris) Fensome et al., p. 30, 31; pl. 3, fig. 5 [middle Miocene (late Serravallian), offshore West Greenland].
- 2016 *Cannosphaeropsis passio* (de Verteuil & Norris) Nøhr-Hansen et al., p. 30; folding fig. 6, appendices 1, 3.14 [middle Miocene (?Langhian–Serravallian), offshore West Greenland].
- 2017** *Cannosphaeropsis passio* (de Verteuil & Norris) Weems et al., fig. 5d, table 1 [middle Miocene (late Serravallian), Virginia].
- 2020 *Cannosphaeropsis passio* (de Verteuil & Norris) Munsterman et al., p. 9 [late Miocene (early Tortonian), Netherlands].
- 2020 *Cannosphaeropsis passio* (de Verteuil & Norris) Louwye et al., p. 143 [middle Miocene (early–middle Serravallian), Belgium].

Remarks: In erecting *Cannosphaeropsis passio*, de Verteuil and Norris (1996) provided a literature review of all previous reports compared or assigned to *Cannosphaeropsis utinensis* which they attributed to their new species. Head and Wrenn (1992) provide discussion of a number of unpublished reports of *Cannosphaeropsis passio*, then regarded as *Cannosphaeropsis utinensis sensu* Brown and Downie, 1985, based on anecdotal accounts from industry workers and other researchers. These include occurrences from Paleocene strata of the southwestern U.S.A. and the Bering Sea (Satchell pers. comm. in Head and Wrenn 1992), strata of Miocene age in the Gulf of Mexico and Gulf of Suez (Wrenn in Head and Wrenn 1992) considered to be allochthonous by de Verteuil (de Verteuil pers. comm. in Head and Wrenn 1992) and strata of late Miocene age in the North Sea (Zevenboom pers. comm. in Head and Wrenn, 1992). The presence of *C. passio* in strata ranging from middle Eocene to late Oligocene has been interpreted as downhole contamination in the study conducted by Köthe (2007).

Of the 42 reports synonymized herein, 19 provide one or more photomicrographs. The specimen illustrated by Brown and Downie (1985) as *Cannosphaeropsis utinensis* was recovered from the late Micoene interval of their studied section while the range base of the species was given as early Eocene (Brown and Downie, 1985, fig. 1). We consider this range base to be questionable with no additional information provided such as whether or not this was based on a single spot occurrence or discussion of the probability of downhole contamination. The unillustrated report of Beiranvand et al. (2014) based on an isolated specimen from the early Paleocene of Iran is similarly questionable. The remaining reports which are assigned or referred to *Cannosphaeropsis utinensis* are deemed questionable, although probable due to their occurrence in Miocene strata.

Cannosphaeropsis quattrocchia Guerstein et al., 2001

- ?1974 *Cannosphaeropsis* sp. Harada & Matsuoka, pl. 2, fig. c [Pliocene, Japan].
- 1981 *Cannosphaeropsis* aff. *utinensis* (Wetzel) Gamarro & Archangelsky, p. 123, 124, 127, 130; pl. 4, fig. 14 tables 1, 2, [early Paleocene (?Danian)–early Miocene (?Aquitania), Argentina].
- ?1988 *Cannosphaeropsis utinensis* (Wetzel) Guerstein & Quattrocchio, p. 30 [early Eocene (?Ypresian)–late Oligocene (?Chattian), Argentina].
- 1990 *Cannosphaeropsis utinensis* (Wetzel) Guerstein, p. 466; pl. 2, figs. 1, 2, 5, table 2 [late Eocene (?Priabonian)–late Oligocene (?Chattian), Argentina].
- ?1991 *Cannosphaeropsis utinensis* (Wetzel) Guerstein & Quattrocchio, p. 147; fig. 8, tables 1, 3 [middle–late Miocene (?Serravallian–Tortonian), Argentina].
- ?1993 *Cannosphaeropsis* cf. *utinensis* (Wetzel) Besems, p. 75, 88; pl. 2, fig. 3 [late middle Miocene (late Tortonian)–late Pliocene (Piacenzian), offshore northwestern Borneo].
- ?1995 *Cannosphaeropsis utinensis* (Wetzel) Guerstein et al., p. 67 [middle Eocene (?Lutetian)–late Oligocene (Chattian), Argentina].
- ?1996 *Cannosphaeropsis utinensis* (Wetzel) Archangelsky, p. 69, 70 [late Eocene (?Priabonian)–early Oligocene (Chattian), Argentina].
- 1998 *Cannosphaeropsis utinensis* (Wetzel) Palamarczuk & Barreda, p. 417; fig. 3, pl. 2, figs. 2, 6, pl. 6, figs. 3, 5, 6 [early Miocene, Argentina].
- 2000a *Cannosphaeropsis utinensis* (Wetzel) Barreda & Palamarczuk, p. 5, 8; fig. 4C [early Miocene, Argentina].
- 2000b *Cannosphaeropsis utinensis* (Wetzel) Barreda & Palamarczuk, p. 113, 117, 119; fig. 3, figs. 13B, 13C, 13E [early Miocene (?late Aquitania–late Burdigalian), Argentina].

- *2001** *Cannosphaeropsis quattrocchiaie* Guerstein et al., p. 155, 156, 158–160, 162; pl. 1, figs. 1–12, pl. 2, figs. 1–8, text-figs. 3, 4a–4h (labelled 1a–4b), appendix 1 [early Miocene (?Aquitanian–Burdigalian), Argentina].
- 2002** *Cannosphaeropsis utinensis* (Wetzel) Barreda, p. 552, 558; figs. 5N, 5N, appendix [early Miocene, Argentina].
- 2002** *Cannosphaeropsis quattrocchiaie* (Guerstein et al.) Guler & Guerstein, p. 363–365; fig. 2, pl. 1, figs. 7–9, table 2 [?late Oligocene (?late Chattian)–early Miocene (?late Burdigalian), Argentina].
- 2003** *Cannosphaeropsis quattrocchiaie* (Guerstein et al.) Guler & Guerstein, p. 34; figs. 2, 11a–11d [?late Oligocene (?late Chattian)–early Miocene (?late Burdigalian), Argentina].
- 2004** *Cannosphaeropsis quattrocchiaie* (Guerstein et al.) Guerstein et al., p. 330, appendix 2 [early Miocene (late Aquitanian–early Burdigalian), Argentina].
- 2007** *Cannosphaeropsis quattrocchiaie* (Guerstein et al.) Musacchio et al., p. 281; fig. 2(15) [?early Miocene, Argentina].
- ?2009** *Cannosphaeropsis utinensis* (Wetzel) Barreda et al., p. 23; fig. 2 [early Miocene (late Aquitanian–early Burdigalian), Argentina].
- 2015** *Cannosphaeropsis quattrocchiaie* (Guerstein et al.) Paredes et al., p. 298; fig. 5B, 5C, table 1, appendix 1 [early Miocene (Burdigalian), Argentina].
- 2018** *Cannosphaeropsis quattrocchiaie* (Guerstein et al.) Premaor et al., p. 21; figs. 8A–8C [?early Miocene, Brasil].
- 2020** *Cannosphaeropsis quattrocchiaie* (Guerstein et al.) Parras et al. p. 7, 12, 17; figs. 5, 6A, appendix 2 [early Miocene (late Aquitanian), Argentina].

Remarks: In erecting *Cannosphaeropsis quattrocchiaie*, Guerstein et al. (2001) effectively reassigned all South American reports formerly compared or assigned to *Cannosphaeropsis utinensis* to their new species. Of the 21 reports synonymized herein, 15 provide one or more photomicrographs. Seven reports, all but one which are unillustrated, represent probable occurrences due to age and geography yet must remain questionable due to their lack of descriptive detail and assignment to *Cannosphaeropsis utinensis*. The report from Japan (Harada and Matsuoka, 1974), while illustrated, remains questionable although probable due to its age and apparent morphology.

***Cannosphaeropsis utinensis* Wetzel, 1933**

- 1932** *Cannosphaeropsis utinensis* Wetzel, nomen nudum, p. 136; pl. 1, fig. 14 [Late Cretaceous, Germany].

- *1933** *Cannosphaeropsis utinensis* Wetzel, p. 6–9; pl. 3, fig. 9–17, text-fig. 12 [Late Cretaceous, Baltic region] [holotype refigured by Sarjeant (1985)].
- 1935 *Cannosphaeropsis utinensis* (Wetzel) Deflandre, p. 223, 224; pl. 8, fig. 1 [Late Cretaceous, France].
- 1937** *Cannosphaeropsis utinensis* (Wetzel) Deflandre, p. 38–40, 52; pl. 16, figs. 12 (*redux* Deflandre, 1935), 13 [Late Cretaceous, France].
- 1938 *Cannosphaeropsis utinensis* (Wetzel) Mercier, p. 95 [Late Cretaceous, France].
- 1940 *Cannosphaeropsis utinensis* (Wetzel) Wetzel, p. 120, 152 [Late Cretaceous, Denmark].
- 1947a *Cannosphaeropsis utinensis* (Wetzel) Deflandre, p. 1574–1576; pl. 1, fig. 1 (*redux* Deflandre, 1935) [Late Cretaceous, France].
- 1947b *Cannosphaeropsis utinensis* (Wetzel) Deflandre, p. 19; pl. 5, fig. 1 (*redux* Deflandre, 1935) [Late Cretaceous, France].
- 1953** *Cannosphaeropsis utinensis* (Wetzel) Wetzel, p. 41; pl. 2, fig. 7 [Late Cretaceous, Baltic region].
- 1957** *Cannosphaeropsis utinensis* (Wetzel) Wetzel, pl. 1, fig. 20 [Late Cretaceous, Denmark].
- 1961** *Cannosphaeropsis utinensis* (Wetzel) Alberti, p. 36; pl. 10, fig. 10 [Late Cretaceous (Coniacian), Germany] [Misidentified, likely assignable to *Adnatosphaeridium filiferum* (Cookson & Eisenack, 1958) Cookson & Eisenack, 1960].
- 1961** *Cannosphaeropsis utinensis* (Wetzel) Evitt, p. 396; pl. 4, fig. 17 [Late Cretaceous (early Turonian–late Coniacian), Pakistan].
- 1961** *Cannosphaeropsis utinensis* (Wetzel) Wetzel, p. 343; pl. 2, fig. 12 [Late Cretaceous, ?Poland].
- 1971 *Cannosphaeropsis utinensis* (Wetzel) Corradini, p. 324, table 1 [Late Cretaceous (middle Campanian–early Maastrichtian), Italy].
- 1971** *Cannosphaeropsis utinensis* (Wetzel) Wilson, p. 1263; pl. 3, fig. 1 [Late Cretaceous (late Campanian–early Maastrichtian), Denmark].
- 1973** *Cannosphaeropsis utinensis* (Wetzel) Kjellström, p. 14; fig. 7, 43 [Late Cretaceous (‘middle’–late Maastrichtian), Sweden].
- 1973** *Cannosphaeropsis utinensis* (Wetzel) Corradini, p. 129, 162, 163; pl. 25, figs. 1, 2, 5, pl. 35, figs. 3a, 3b, 4, table 1 [Late Cretaceous (middle Campanian–early Maastrichtian), Italy].
- 1974 *Cannosphaeropsis utinensis* (Wetzel) Jenkins et al., appendix 1 [Late Cretaceous (Campanian), offshore eastern Canada].
- 1974 *Cannosphaeropsis utinensis* (Wetzel) Riegel, p. 349; table 1 [Late Cretaceous (Campanian–Danian), Spain].
- 1974 *Cannosphaeropsis utinensis* (Wetzel) Upshaw et al., p. 1132 [Late Cretaceous, offshore eastern Canada].

- ?1975 *Cannosphaeropsis utinensis* (Wetzel) de Coninck, p. 25, 54; pl. 21, figs. 25–28 [early Eocene (Ypresian), Belgium].
- 1975a *Cannosphaeropsis utinensis* (Wetzel) Foucher, pl. 2, fig. 9, tables 1, 2 [Late Cretaceous (middle–late Santonian), France].
- 1975b *Cannosphaeropsis utinensis* (Wetzel) Foucher, p. 10 [Late Cretaceous (Santonian), France].
- 1975 *Cannosphaeropsis utinensis* (Wetzel) Gradstein et al., p. 118 [Late Cretaceous (Campanian), offshore eastern Canada].
- 1975 *Cannosphaeropsis utinensis* (Wetzel) Jan du Chêne et al., fig. 7, pl. 2, fig. 16 [late Paleocene (late Thanetian), France].
- 1975a *Cannosphaeropsis utinensis* (Wetzel) Williams, pl. 5, fig. 2 [Late Cretaceous (Campanian), offshore eastern Canada].
- 1975b *Cannosphaeropsis utinensis* (Wetzel) Williams, p. 126; fig. 13, pl. 1, fig. 15, folding fig. 5 [Late Cretaceous (Campanian–Danian), offshore eastern Canada].
- 1976a *Cannosphaeropsis utinensis* (Wetzel) Foucher, p. 215, 216, 218 [Late Cretaceous (middle–late Santonian), France].
- 1976b *Cannosphaeropsis utinensis* (Wetzel) Foucher, p. 6, 16, 27 [Late Cretaceous (early–middle Santonian), France].
- 1976 *Cannosphaeropsis utinensis* (Wetzel) Schumacker-Lambry & Chateauneuf, p. 274 [late Paleocene (early Thanetian), Belgium].
- 1977 *Cannosphaeropsis utinensis* (Wetzel) Williams & Bujak, p. 17; text-fig. 9 [Late Cretaceous (Campanian–Danian), offshore eastern Canada].
- 1977 *Cannosphaeropsis utinensis* (Wetzel) Foucher & Robaszynski, p. 11, 29; pl. 1, fig. 6, 7, table 1 [Late Cretaceous (early Maastrichtian), Belgium].
- ^R1977 *Cannosphaeropsis utinensis* (Wetzel) Schumacker-Lambry, p. 50 [late Paleocene, Belgium]
- 1978 *Cannosphaeropsis utinensis* (Wetzel) Bujak & Williams, p. 8 [Late Cretaceous (Santonian–Campanian), offshore eastern Canada].
- ^R1978 *Cannosphaeropsis utinensis* (Wetzel) Schumacker-Lambry, p. 33, 36, pl. 1, fig. 11 [late Paleocene, Belgium].
- 1978 *Cannosphaeropsis utinensis* (Wetzel) Steinkraus, p. 35 [Late Cretaceous (Maastrichtian), offshore Georgia].
- 1979 *Cannosphaeropsis utinensis* (Wetzel) Antonescu & Alexandrescu, p. 74, 78, 84, 86 [Late Cretaceous (late Maastrichtian), Romania].

- 1979 *Cannosphaeropsis utinensis* (Wetzel) Barss et al., p. 13, 19, 27, 38, 41, 42, 44, 49, 53, 63, 75, 76, 78, 86, appendix [Late Cretaceous (Santonian)–early Paleocene (Danian), offshore eastern Canada].
- ^R1979 *Cannosphaeropsis utinensis* (Wetzel) Barss et al., p. 13, 19, 27, 38, 41, 42, 44, 49, 53, 63, 75, 76, 78, 86, appendix [middle Miocene, offshore eastern Canada].
- 1979 *Cannosphaeropsis utinensis* (Wetzel) Foucher, p. 95; tables 1, 3 [Late Cretaceous (middle–late Santonian), France].
- 1979a *Cannosphaeropsis utinensis* (Wetzel) Hansen, p. 139 [early Paleocene (Danian), Denmark].
- 1979b *Cannosphaeropsis utinensis* (Wetzel) Hansen, p. 141 [early Paleocene (Danian), Denmark].
- ?1979 *Cannosphaeropsis utinensis* (Wetzel) Zavada, p. 40; pl. 1, fig. 10 [Late Cretaceous, North Macedonia].
- 1980 *Cannosphaeropsis utinensis* (Wetzel) de Coninck, pl. 1, figs. 7–8, table 1 [early Eocene (Ypresian), Belgium].
- 1980 *Cannosphaeropsis utinensis* (Wetzel) May, p. 21, 22, 25, 45; pl. 2, figs. 1, 2, range charts 1, 2, appendix [Late Cretaceous (?latest Campanian–earliest Maastrichtian), New Jersey].
- 1981 *Cannosphaeropsis utinensis* (Wetzel) Colin et al., p. 126 [Late Cretaceous (‘Senonian’; ?Coniacian–Campanian), offshore Ireland].
- 1981 *Cannosphaeropsis utinensis* (Wetzel) Azema et al., p. 243; fig. 3, pl. 1, fig. 2, 3 [Late Cretaceous (late Santonian–?early Campanian), ?France].
- 1982 *Cannosphaeropsis utinensis* (Wetzel) Burger, table 3 [Late Cretaceous (early Albian), Australia].
- 1982 *Cannosphaeropsis utinensis* (Wetzel) Rauscher & Doubinger, p. 103 [Late Cretaceous (late Campanian), Morocco].
- 1983 *Cannosphaeropsis utinensis* (Wetzel) Foucher, p. 25; pl. 3, fig. 6, table 1b [Late Cretaceous (middle–late Santonian), France].
- ?1984 *Cannosphaeropsis* cf. *utinensis* (Wetzel) Schrank, p. 195 [Late Cretaceous (Maastrichtian), Egypt].
- 1985 *Cannosphaeropsis utinensis* (Wetzel) Hultberg, p. 111, 112; pl. 2, fig. A [Late Cretaceous (late Maastrichtian), Denmark, Sweden].
- 1985 *Cannosphaeropsis utinensis* (Wetzel) Masure, p. 205; fig. 3, appendix 2 [Late Cretaceous (early Maastrichtian), France].
- 1985 *Cannosphaeropsis utinensis* (Wetzel) Robaszynski et al., p. 32; fig. 21 [Late Cretaceous (early Maastrichtian, Netherlands)].
- ?1985 *Cannosphaeropsis* cf. *utinensis* (Wetzel) Schrank & Perch-Nielsen, fig. 3 [Late Cretaceous (Maastrichtian), Egypt].

- 1986** *Cannosphaeropsis utinensis* (Wetzel) Marheinecke, p. 18, 19, 39; fig. 7.3, pl. 1, fig. 7, pl. 13, fig. 8 [Late Cretaceous (late Maastrichtian), Germany].
- 1987 *Cannosphaeropsis utinensis* (Wetzel) Athersuch, p. 6; fig. 2 [Late Cretaceous (early Coniacian), offshore United Arab Emirates].
- 1987 *Cannosphaeropsis utinensis* (Wetzel) Rademakers, p. 71, 72; fig. 1 (*redux* Wetzel, 1933) [Late Cretaceous (late Campanian–late Maastrichtian), Belgium].
- 1987** *Cannosphaeropsis utinensis* (Wetzel) Schrank, p. 263; pl. 10, fig. 2, tables 4, 5 [Late Cretaceous (Maastrichtian), Egypt].
- 1987** *Cannosphaeropsis utinensis* (Wetzel) Tocher, p. 419; fig. 2, pl. 1, fig. 12, appendix [Late Cretaceous (latest Campanian–earliest Maastrichtian), offshore New Jersey].
- 1988 *Cannosphaeropsis utinensis* (Wetzel) McMinn, p. 142, 145 [Late Cretaceous (early Coniacian–early Maastrichtian), offshore western Australia].
- 1988 *Cannosphaeropsis utinensis* (Wetzel) Schrank, p. 137 [Late Cretaceous (Maastrichtian), Egypt].
- 1989 *Cannosphaeropsis utinensis* (Wetzel) Aurisano, text-figs. 11–13 [Late Cretaceous (early Campanian–late Maastrichtian), New Jersey].
- 1989 *Cannosphaeropsis utinensis* (Wetzel) Heilmann-Clausen & Costa, p. 456; fig. 1 [early Eocene (Ypresian), Germany].
- 1989** *Cannosphaeropsis utinensis* (Wetzel) Riding & Davey, pl. 1, fig. 11 [Late Cretaceous (late Campanian), England].
- 1990 *Cannosphaeropsis utinensis* (Wetzel) Begouen et al., 1990, p. 1383 [Late Cretaceous (late Campanian), France].
- 1990 *Cannosphaeropsis utinensis* (Wetzel) Ertuğ et al., p. 188; pl. 5, fig. C [Late Cretaceous (late Maastrichtian)–early Paleocene (early Danian), Turkey].
- 1990** *Cannosphaeropsis utinensis* (Wetzel) Harker et al., p. 91, 92, 190; pl. 12, fig. 1, text-figs. 35, 38 [Late Cretaceous (early Campanian), Saskatchewan, Wyoming, Texas,].
- 1990** *Cannosphaeropsis utinensis* (Wetzel) Wheeler & Sarjeant, p. 300, 301, 333; pl. 4, fig. Cretaceous (Campanian), Iran].
- 1991** *Cannosphaeropsis utinensis* (Wetzel) Kirsch, p. 58, 150, 151, 166, 168, 169, 171; figs. 65–68, 71, pl. 4, 1–4, 6 [Late Cretaceous (late Campanian–early Maastrichtian), Germany].
- 1991 *Cannosphaeropsis utinensis* (Wetzel) Köthe, fig. 4 [Late Cretaceous (late Maastrichtian), Germany].
- 1992** *Cannosphaeropsis utinensis* (Wetzel) Marheinecke, p. 41, 42; pl. 6, figs. 4, 6, tables 1, 2 [Late Cretaceous (early–late Maastrichtian), Germany].

- 1992** *Cannosphaeropsis utinensis* (Wetzel) Oloto, p. 442; pl. 1, fig. 11 [early Eocene (Ypresian), offshore Nigeria] [possibly misidentified *Adnatosphaeridium* sp.].
- 1992 *Cannosphaeropsis utinensis* (Wetzel) Mao & Mohr, table 1, appendix A [Late Cretaceous (early Maastrichtian, southern Indian Ocean)].
- 1993 *Cannosphaeropsis utinensis* (Wetzel) Fraser et al., figs. 5j, 5k [Late Cretaceous (early late–Campanian), Indonesia].
- 1993 *Cannosphaeropsis utinensis* (Wetzel) Moshkovitz & Habib, p. 177; text-fig. 8, table 3 [Late Cretaceous (earliest Danian), Alabama].
- 1993** *Cannosphaeropsis utinensis* (Wetzel) Schiøler & Wilson, p. 341, 343–345; fig 2, pl. 2, fig. 10, tables 1, 2 [Late Cretaceous (late early–early late Maastrichtian), North Sea].
- 1994 *Cannosphaeropsis utinensis* (Wetzel) Eshet et al., p. 6, 10, 14, 15; figs. 2, 4, 6–8, table 1 [Late Cretaceous (late Campanian–early Maastrichtian), Israel].
- 1994** *Cannosphaeropsis utinensis* (Wetzel) Kurita & Obuse, fig. 4(10), fig. 5, table 1 [late Paleocene (Thanetian), Japan].
- 1995** *Cannosphaeropsis utinensis* (Wetzel) Pavlishina, p. 132, 140; pl. 2, fig. 5 [Late Cretaceous (Maastrichtian), Bulgaria].
- 1995 *Cannosphaeropsis utinensis* (Wetzel) Rademakers, p. 131; figs. 2(3) (*redux* Wetzel, 1933), 3 [Late Cretaceous (late Maastrichtian, Belgium, Netherlands)].
- 1995 *Cannosphaeropsis utinensis* (Wetzel) Robinson et al., appendix [Late Cretaceous (late Santonian–?late Campanian), Turkey].
- 1995** *Cannosphaeropsis utinensis* (Wetzel) Schrank & Ibrahim, p. 14; text-fig. 6, pl. 9, fig. 4 [Late Cretaceous (late early Maastrichtian), Egypt].
- ?1995 *Cannosphaeropsis utinensis* (Wetzel) Srivastava, p. 272; pl. 6, figs. 3–6 [Late Cretaceous (Campanian), Texas] [possibly misidentified *Adnatosphaeridium* sp.]
- 1996 *Cannosphaeropsis utinensis* (Wetzel) Abdel-Kireem et al., p. 104; fig. 5 [Late Cretaceous (Campanian–Maastrichtian), Denmark].
- 1996** *Cannosphaeropsis utinensis* (Wetzel) Herngreen et al., p. 32; plate 1, fig. 1, tables 4, 9 [Late Cretaceous (middle Cenomanian–late Campanian), Netherlands] [misidentified, likely *Nematosphaeropsis* sp.].
- 1996** *Cannosphaeropsis utinensis* (Wetzel) Hoek et al., p. 132, 133, 136, 138; pl. 3, fig. 1, text-figs. 2–5, table 1 [Late Cretaceous (late Campanian–earliest late Maastrichtian), Israel].
- 1996** *Cannosphaeropsis utinensis* (Wetzel) Siegl-Farkas & Wagreich, p. 25; fig. 2, pl. 2, fig. 3 [Late Cretaceous (late Campanian), Hungary].

- 1997 *Cannosphaeropsis utinensis* (Wetzel) Gedl, p. 208; appendix [Late Cretaceous (early Albian), Poland].
- 1997** *Cannosphaeropsis utinensis* (Wetzel) Fechner et al., pl. 1, figs. 1–3, table 1 [early Eocene (late Ypresian), Germany] [misidentified, likely *Nematosphaeropsis* sp.].
- ^R1997 *Cannosphaeropsis utinensis* (Wetzel) Riding, Moorlock et al., p. 30 [Pleistocene, England].
- 1997a *Cannosphaeropsis utinensis* (Wetzel) Roncaglia & Corradini, fig. 4, table 1 [Late Cretaceous (early Maastrichtian), Italy].
- 1997b *Cannosphaeropsis utinensis* (Wetzel) Roncaglia & Corradini, figs. 3–9, table 1 [Late Cretaceous (late Campanian–late Maastrichtian), Italy].
- 1997 *Cannosphaeropsis utinensis* (Wetzel) Schiøler et al., fig. 5a, appendices A, B [Late Cretaceous (late Maastrichtian), Netherlands].
- 1997** *Cannosphaeropsis utinensis* (Wetzel) Siegl-Farkas p. 81, 86; pl. 6, fig. 5 (*redux* Siegl-Farkas & Wagreich, 1996) [Late Cretaceous (late Campanian), Hungary].
- ^R1998 *Cannosphaeropsis utinensis* (Wetzel) Waterhouse, appendix A [early Pliocene, Papua New Guinea].
- 1999 *Cannosphaeropsis utinensis* (Wetzel) de Coninck; pl. 6, figs. 11–13 [early Eocene (Ypresian), Belgium].
- 1999 *Cannosphaeropsis utinensis* (Wetzel) Prince et al., fig. 2, table 1, appendix A [Late Cretaceous (late Santonian–early Campanian), England].
- 2000 *Cannosphaeropsis utinensis* (Wetzel) Slimani, p. 17; tables 1–3, 5 [Late Cretaceous (late Campanian–early Maastrichtian), Belgium].
- 2001 *Cannosphaeropsis utinensis* (Wetzel) Schiøler & Wilson, fig. 1 [Late Cretaceous (late Campanian–early Maastrichtian), France].
- 2001a** *Cannosphaeropsis utinensis* (Wetzel) Antonescu et al., p. 235, 237; pl. 1, fig. 9, pl. 3, fig. 68, table 1 [Late Cretaceous (late Campanian–early Maastrichtian), France].
- 2001b *Cannosphaeropsis utinensis* (Wetzel) Antonescu et al., p. 261, appendix 1 [Late Cretaceous (late Campanian–early Maastrichtian), France].
- 2001 *Cannosphaeropsis utinensis* (Wetzel) Slimani, p. 179, 185, 186; fig. 8c, text-fig. 11, appendix 1 [Late Cretaceous (late Campanian–late Maastrichtian), Belgium].
- 2002 *Cannosphaeropsis utinensis* (Wetzel) Mehrotra et al., p. 83 [Late Cretaceous (late Maastrichtian), offshore India].
- 2002 *Cannosphaeropsis utinensis* (Wetzel) Reich & Frenzel, p. 108, 276 [Late Cretaceous (early Maastrichtian), Germany].

- 2002** *Cannosphaeropsis utinensis* (Wetzel) Roncaglia, p. 67, 72; figs. 3, 5, appendix [Late Cretaceous (late Campanian–early Maastrichtian), Italy].
- 2003** *Cannosphaeropsis utinensis* (Wetzel) Torricelli & Amore, p. 510; figs. 4, 5, pl. 3, figs. 22, 23 [Late Cretaceous (late Campanian–?early Maastrichtian), Italy].
- ^R2004 *Cannosphaeropsis utinensis* (Wetzel) Gedl, p. 259; fig. 2, appendix [Late Cretaceous (Maastrichtian–early Danian), Czech Republic]
- 2004 *Cannosphaeropsis utinensis* (Wetzel) Pavlishina et al. p. 77, 80, 84; tables 1, 6 [Late Cretaceous (late Santonian–middle Campanian), Austria].
- 2004** *Cannosphaeropsis utinensis* (Wetzel) Riding & Kyffin-Hughes, p. 28; 31; fig. 4E, appendix 3 [Late Cretaceous (late Campanian–early Maastrichtian), England].
- 2006 *Cannosphaeropsis utinensis* (Wetzel) Garg et al., p. 743; figs. 3, 7 [Late Cretaceous (?late Campanian–Maastrichtian), India].
- 2006** *Cannosphaeropsis utinensis* (Wetzel) Ghasemi-Nejad et al., p. 830; fig. 3, 4L [Late Cretaceous (early–late Maastrichtian), Iran].
- 2006 *Cannosphaeropsis utinensis* (Wetzel) Williams, p. 4; fig. 1, appendix A [Late Cretaceous (late Maastrichtian), offshore eastern Canada].
- 2006 *Cannosphaeropsis utinensis* (Wetzel) Zosimovish et al., p. 204; fig. 3 [Late Cretaceous (late Campanian–early Maastrichtian), Ukraine].
- 2007** *Cannosphaeropsis utinensis* (Wetzel) Olszewska-Nejbert & Barski, p. 99; fig. 2B [Late Cretaceous (Santonian–Maastrichtian), Poland].
- 2008 *Cannosphaeropsis utinensis* (Wetzel) Aleksandrova & Zaporozhets, p. 308; table 1 [Late Cretaceous (late Campanian), Russia].
- 2008 *Cannosphaeropsis utinensis* (Wetzel) Fensome et al., appendix 2 [Late Cretaceous (late Campanian), Scotian Margin].
- 2008** *Cannosphaeropsis utinensis* (Wetzel) Smelror et al., p. 68; pl. 2, fig. 1, appendices 1, 2 [Late Cretaceous (middle Campanian–?early Maastrichtian), Mozambique].
- ^R2009 *Cannosphaeropsis utinensis* (Wetzel) De Schepper & Head, p. 194, text-fig. 5 [Pliocene–Pleistocene, northeast Atlantic].
- 2009 *Cannosphaeropsis utinensis* (Wetzel) Rabbani et al., p. 5, 6; figs. 2, 3 [Late Cretaceous (Campanian)–early Paleocene (early Danian), Iran].
- 2009** *Cannosphaeropsis utinensis* (Wetzel) Soliman et al., p. 406, 409; pl. 1, fig. 3, appendix [Late Cretaceous (late Campanian–early Maastrichtian), Austria].
- ^R2009 *Cannosphaeropsis utinensis* (Wetzel) Zhao & Morzadec-Kerfourn, p. 197 [Pleistocene, northwest Pacific].

- ?2010 *Cannosphaeropsis utinensis* (Wetzel) Abd El-Gawwad et al., p. 3532; pl. 3, fig. 15 [Late Cretaceous (late Campanian–early Maastrichtian), United Arab Emirates] [figured specimen indiscernable].
- 2010 *Cannosphaeropsis utinensis* (Wetzel) Mehrotra et al., fig. 9, appendix 1 [Late Cretaceous (late Maastrichtian), India].
- 2010 *Cannosphaeropsis utinensis* (Wetzel) Moradian & Allameh, p. 920 [Late Cretaceous (late Turonian–early Santonian), Iran].
- 2011 *Cannosphaeropsis utinensis* (Wetzel) Allameh et al., p. 69 [Late Cretaceous (Aptian), Kazakhstan].
- 2011 *Cannosphaeropsis utinensis* (Wetzel) Slimani et al., p. 142–144, 153, 155; fig. 4a, table 1, appendix A [Late Cretaceous (middle Campanian–late Maastrichtian), Belgium].
- 2012 *Cannosphaeropsis utinensis* (Wetzel) Aleksandrova et al., pl. 7, fig. 10, table 1 [Late Cretaceous (late Campanian), Russia].
- 2012 *Cannosphaeropsis utinensis* (Wetzel) Egger et al., fig. 5(4–6), table 1 [Late Cretaceous (early Campanian), Austria].
- 2012 *Cannosphaeropsis utinensis* (Wetzel) Mohamed et al., p. 159; fig. 8C, table 1 [Late Cretaceous (late Maastrichtian), Austria].
- ^R2012 *Cannosphaeropsis utinensis* (Wetzel) Mohamed et al., p. 159 [early Paleocene (early Danian), Austria].
- 2012 *Cannosphaeropsis utinensis* (Wetzel) Senemari, p. 76 [Late Cretaceous (late Campanian–early Danian), Iran].
- 2012 *Cannosphaeropsis utinensis* (Wetzel) Sheldon et al., p. 13, fig. 3Æ [Late Cretaceous (Campanian–Maastrichtian), Denmark].
- 2013 *Cannosphaeropsis utinensis* (Wetzel) King et al., p. 9, text-fig. 14 [early Eocene (early Ypresian), Kazakhstan].
- 2013 *Cannosphaeropsis utinensis* (Wetzel) Surlyk et al., p. 241, appendix 1 [Late Cretaceous (late Campanian–late Maastrichtian), Denmark].
- 2014 *Cannosphaeropsis utinensis* Beiranvand et al., p. 250; fig. 4, table 2 [Late Cretaceous (late Maastrichtian), Iran].
- 2014 *Cannosphaeropsis utinensis* (Wetzel) Deaf et al., pl. 3, fig. 17, appendix 2 [Late Cretaceous (middle–late Cenomanian), Egypt].
- 2014 *Cannosphaeropsis utinensis* (Wetzel) El-Soughier et al., fig. 2, pl. 3, fig. 10, appendix [Late Cretaceous (?Campanian–Maastrichtian), Egypt] [possibly misidentified *Adnatosphaeridium* sp.].

- 2014** *Cannosphaeropsis utinensis* (Wetzel) Radmacher et al., p. 313, 318; fig. 7(2) [Late Cretaceous (late Campanian–late Maastrichtian), Spain].
- 2015 *Cannosphaeropsis utinensis* (Wetzel) Pervushov et al., fig. 16 [Late Cretaceous (late Campanian), Russia].
- ?2015 *Cannosphaeropsis quattrocchiaie* (Wetzel) Rabbani et al., table 1 [early Eocene (Ypresian), Iran].
- 2015** *Cannosphaeropsis utinensis* (Wetzel) Radmacher et al., p. 30; fig. 4, 5, pl. 1, fig. 3, supp. tables 1, 3 [Late Cretaceous (late Maastrichtian), Norwegian Sea].
- 2017** *Cannosphaeropsis utinensis* (Wetzel) Allameh et al., p. 123, 127, 134; fig. 2, pl. 1, fig. 13 [Late Cretaceous (Maastrichtian), Iran].
- ^R2017 *Cannosphaeropsis utinensis* (Wetzel) Mohamed & Piller, p. 39 [early Paleocene (early Danian), Austria].
- ^R2017 *Cannosphaeropsis utinensis* (Wetzel) Țabără & Slimani, p. 41; table 1 [Late Cretaceous (late Maastrichtian), Romania].
- 2018** *Cannosphaeropsis utinensis* (Wetzel) Jedavi et al., p. 3, 4, 7; fig. 5, pl. 2, fig. 4 [Late Cretaceous (latest Campanian), Iran].
- 2018** *Cannosphaeropsis utinensis* (Wetzel) King et al., p. 179; pl. 8, figs. 4, 5 [early Eocene (Ypresian), Crimea].
- 2019** *Cannosphaeropsis utinensis* (Wetzel) Mohamed et al., p. 16, 18; fig. 4N [Late Cretaceous (early–late Maastrichtian), Egypt].
- 2019** *Cannosphaeropsis utinensis* (Wetzel) Santos et al., fig. 3, pl. 3, fig. 1, table 1 [Late Cretaceous (early Turonian), Brasil].
- 2019** *Cannosphaeropsis utinensis* (Wetzel) Soliman & Slimani, p. 239, 245; fig. 6N, appendix A, B (table 1) [Late Cretaceous (late Maastrichtian), Egypt].
- 2020 *Cannosphaeropsis utinensis* (Wetzel) Amano & Kurita, p. 52; table 1 [middle Paleocene (late Selandian), Japan].
- 2020 *Cannosphaeropsis utinensis* (Wetzel) Amiri & Zarei, p. 84 [Late Cretaceous (middle Campanian–late Maastrichtian), Iran].
- ?2020 *Cannosphaeropsis utinensis* (Wetzel) Farmani et al., fig. B appendix 4 [Late Cretaceous (late Campanian–?Selandian), Iran] [possibly misidentified *Adnatosphaeridium* sp.].
- 2020** *Cannosphaeropsis utinensis* (Wetzel) Iakovleva & Heilmann-Clausen, fig. 5, pl. 3, fig. 2 [early Eocene (late Ypresian), Kazakhstan].
- ?2020 *Cannosphaeropsis utinensis* (Wetzel) Kaya et al., p. 10 [Late Cretaceous (?late Santonian), Tajikistan].

- 2020** *Cannosphaeropsis utinensis* (Wetzel) Baraboshkin et al., p. 830, 832, 842; figs. 3, 7–9, pl. 6, fig. 6 [Late Cretaceous (lower lower Maastrichtian–lower upper Maastrichtian), Russia].
- 2020** *Cannosphaeropsis utinensis* (Wetzel) Pearce et al., p. 47, 50, 58; figs. 17f, 18, 21, pl. 1, fig. 5, appendices A, B, supp. tables 2, 3 [Late Cretaceous (late Santonian–early Campanian), England].
- 2020** *Cannosphaeropsis utinensis* (Wetzel) Radmacher et al., p. 3, 8 [Late Cretaceous (late Campanian–late Maastrichtian), Spain].
- 2021** *Cannosphaeropsis utinensis* (Wetzel) González Estebenet et al., tables 1, 3 [early Paleocene (Danian), Argentina].
- 2021a** *Cannosphaeropsis utinensis* (Wetzel) Slimani et al., pl. 1, fig. 20 [Late Cretaceous (late Campanian), Morocco].
- 2021b** *Cannosphaeropsis utinensis* (Wetzel) Slimani et al., table 1 [Late Cretaceous (late Campanian), Poland].

Remarks: The record of *Cannosphaeropsis quattrocchia* from the early Eocene strata of Iran (Rabbani et al., 2015) is considered to be that of *Cannosphaeropsis utinensis* reported in error given the provision of Wetzel (1933) as the original author. The report of *C. utinensis* from North Macedonia (Zavada, 1979) is considered questionable as the figured specimen resembles a phytoclast while the description asserts the general adherence of the studied material to the original species description. Of the 162 reports synonymized herein, 71 provide one or more photomicrographs and all but one of these illustrated reports are accepted as allochthonous occurrences while nine are deemed questionable or misidentifications. Although unpublished, Wilson (1974) detailed the occurrence of *C. utinensis* in the Late Cretaceous (late Campanian–late Maastrichtian) strata of Denmark in his PhD thesis (Wilson, 1974, p. 242, 243, 430; pl. 30, figs. 1, 2, table 3).

***Cannosphaeropsis williamsii* Sarjeant, 1986**

- ?1966** *Cannosphaeropsis reticulensis* (Pastiels) Morgenroth, p. 19; pl. 4, figs. 2, 3 [early Eocene (Ypresian), Belgium].
- 1966** *Cannosphaeropsis reticulensis* (Pastiels) Williams & Downie, p. 223; pl. 24, fig. 8 [early Eocene (Ypresian), England].
- 1968** *Adnatosphaeridium reticulense* (Pastiels) de Coninck; pl. 11, figs. 25, 26 [early Eocene (Ypresian), Belgium].
- 1975** *Adnatosphaeridium reticulense* (Pastiels) Williams & Brideaux, p. 20–22, 28; pl. 21, fig. 11, folding figs. 8, 9, 11, 14, 15b, appendix [early Paleocene (Danian)–middle Eocene (Lutetian), offshore eastern Canada].

- 1975** *Cannosphaeropsis reticulensis* (Pastiels) (*sensu* Williams & Downie) Williams & Brideaux, pl. 36, fig. 2, folding fig. 12, appendix [late Eocene (?Priabonian), offshore eastern Canada].
- 1978** *Adnatosphaeridium reticulense* (Pastiels) Schumacker-Lambry, p. 35, 45; pl. 1, fig. 8 [late Paleocene (Thanetian)–early Oligocene (Rupelian), Belgium].
- 1980** *Adnatosphaeridium reticulense* (Pastiels) Châteauneuf, p. 132, 164, , 177, 182, 190, 192, 256, 274, 290, 297, 323; figs. 57, 61a, pl. 19, fig. 2, text-figs. 34b, 35b [early–late Eocene (Bartonian)–early Oligocene (early Rupelian), France].
- *1986 *Cannosphaeropsis williamsii* Sarjeant, p. 33, 34; [early Paleocene (Danian)–middle Eocene (Lutetian), aforementioned records].

Remarks: *Cannosphaeropsis williamsii* is perhaps the most questionable and poorly understood species among those presently accepted within the genus. Uncertainty with respect to its tabulation and lack of autophragm sutural ridges lead Sarjeant (1986) to exclude this form from *Nematosphaeropsis* even though the intricate, slender trabecular network is otherwise akin to the morphology typical of the genus. In erecting *C. williamsii* based on specimens assigned to *Adnatosphaeridium* (now *Nematosphaeropsis*) *reticulensis* Pastiels, 1948, Sarjeant (1986) expressed a tentative chronostratigraphic range for the species as early Paleocene (Danian)–middle Eocene (Lutetian) based on known records.

Genus: ***Hafniasphaera***

All species (only allochthonous reports with photographs)

- 1967** *Baltisphaeridium septatum* Cookson & Eisenack, p. 253, 254; pl. 42, figs. 6–10; text-fig. 1 [late Paleocene, Australia].
- 1977** *Hafniasphaera cryptovesiculata* Hansen, p. 14, 15; figs. 9–10, 18C, 18E, 18F, 19A–B [early Paleocene (Danian), Denmark].
- 1977** *Hafniasphaera fluens* Hansen, p. 16; figs. 13, 14, 19C–D [Late Cretaceous (late Maastrichtian)–early Paleocene (Danian), Denmark].
- 1977** *Hafniasphaera graciosa* Hansen, p. 15, figs. 11, 12, 18B, D [early Paleocene (Danian), Denmark].
- 1977** *Hafniasphaera hyalospinosa* Hansen, p. 14; figs. 7, 8, 18A [early Paleocene (Danian), Denmark].
- 1977** *Hafniasphaera septata* (Cookson & Eisenack) Hansen, p. 16; figs. 22A–E [early-middle Paleocene (Danian–Selandian), Denmark].
- 1982** *Hafniasphaera goodmanii* Edwards, p. 110, 112, 113; pl. 1, figs. 1–3, 5, 6, 8, 9 [early Eocene (Ypresian), Maryland, Virginia, Georgia].

- 1982** *Hafniasphaera hyalospinosa* (Hansen) Raucher & Doubinger, p. 103; pl. 2, fig. 9 [Late Cretaceous (Maastrichtian), Morocco].
- 1984** *Hafniasphaera goodmanii* (Edwards) Edwards et al., p. 142; pl. 4, fig. 8, text-fig. 2 [early Eocene (Ypresian), Virginia].
- 1984** *Hafniasphaera fluens* (Hansen) Helenes, p. 104; pl. 3, figs. 1–3 [Late Cretaceous (Maastrichtian), Baja California].
- 1985** *Hafniasphaera cryptovesiculata* (Hansen) Hultberg, p. 127; pl. 5, Fig. F [early Paleocene (late Danian), Denmark, Sweden].
- 1985** *Hafniasphaera graciosa* (Hansen) Hultberg, p. 128; pl. 5, Fig. G, H [early Paleocene (late Danian), Denmark, Sweden].
- 1985** *Hafniasphaera hyalospinosa* (Hansen) Hultberg, p. 129; pl. 6, fig. A [early Paleocene (Danian), Denmark, Sweden].
- 1985** *Hafniasphaera septata* (Cookson & Eisenack) Hultberg, p. 130; pl. 6, fig. B–D [early Paleocene (middle–late Danian), Denmark, Sweden].
- 1985** *Hafniasphaera fluens* (Hansen) Hultberg, p. 130, 131; pl. 6, fig. E [Late Cretaceous (late Maastrichtian)–early Paleocene (Danian), Denmark, Sweden].
- 1985** *Hafniasphaera graciosa* (Hansen) Thomson & Heilmann-Clausen, p. 347; pl. 5, figs. 7–9 [Danian, Denmark].
- 1985** *Hafniasphaera septata* (Cookson & Eisenack) Williams & Bujak, p. 877, 894, 905; fig. 19, fig. 29(13, *redux* Cookson & Eisenack, pl. 42, fig. 6) [early Paleocene (Danian)–early Eocene (Ypresian), data synthesis].
- 1985** *Hafniasphaera* sp. Zalinskaya & Naidin, pl. 2, fig. 3 (fig. 1 in caption) [Late Cretaceous (late Maastrichtian), Russia].
- 1986** *Hafniasphaera cryptovesiculata* (Hansen) Hultberg, p. 38, 40; fig. 2, pl. 1, fig. 5 [early Paleocene (late Danian), Denmark, Sweden].
- 1986** *Hafniasphaera* sp. A Powell, pl. 5, fig. 1, text-fig. 6 [late Oligocene (Chattian)–early Miocene (Aquitania), Italy].
- 1987** *Hafniasphaera* sp. cf. *H. fluens* (Hansen) Jan du Chêne, p. 157, 170; pl. 24, figs. 1–3, 14 [Danian, Senegal].
- 1988** *Hafniasphaera fluens* (Hansen) Soncini & Rauscher, p. 431, 433, 449; pl. 3, fig. 12 [Late Cretaceous (early Maastrichtian), Paleocene (Danian, Thanetian), Morocco].
- 1988** *Hafniasphaera septata* (Cookson & Eisenack) Wilson, p. 21; pl. 10, fig. 3 [middle Paleocene (Selandian)–early Eocene (Ypresian), New Zealand].
- 1988** *Hafniasphaera* sp. Wilson, pl. 10, figs. 2a, 2b [early Eocene (Ypresian), New Zealand].

- 1989** *Hafniasphaera granulata* Mao, p. 139; pl. 28, figs. 9–10 [Quaternary, South China Sea; now ?*Achomosphaera* (Londix et al., 2018)].
- 1990** *Hafniasphaera cryptovesiculata* (Hansen) Oloto, p. 27; pl. 3, fig. 5 [early Paleocene (late Danian), Nigeria].
- 1991** *Hafniasphaera cryptovesiculata* (Hansen) Köthe, p. 11, 46; pl. 28 [early Paleocene (Danian), Germany].
- 1991** *Hafniasphaera fluens* (Hansen) Köthe, p. 46; figs. 4, 5, pl. 2, fig. 4, pl. 5, fig. 1, pl. 11, fig. 4, pl. 29, (part 1, 2) [early Paleocene (early Danian), Germany].
- 1991** *Hafniasphaera goodmanii* (Edwards) Köthe, p. 46; fig. 5, pl. 5, fig. 2, pl. 29 (part 1) [late Paleocene (Thanetian), Germany].
- 1991** *Hafniasphaera graciosa* (Hansen) Köthe, p. 46; figs. 4, 5, pl. 29 (part 1, 3) [Paleocene (Danian, Thanetian), Germany].
- 1991** *Hafniasphaera septata* (Cookson & Eisenack) Köthe, p. 14, 46; figs. 2–6, pl. 13, fig. 13, pls. 28, 29 (parts 1–3) [Paleocene (Danian, Thanetian)–early Eocene (Ypresian?), Germany].
- 1993** *Hafniasphaera* sp. Besems, p. 75, 88; pl. 4, fig. 2 [late Pliocene (Piacenzian), offshore Borneo].
- 1998** *Hafniasphaera septata* (Cookson & Eisenack) Edwards, fig. 3, pl. 1, fig. 11 [late Paleocene (Thanetian), South Carolina].
- 2001** *Hafniasphaera goodmanii* (Edwards) Edwards, p. G8, G12, G16; fig. 4, pl. 3, fig. 1 [early Eocene (?Ypresian), Georgia].
- 2001** *Hafniasphaera septata* (Cookson & Eisenack) Edwards, p. G3, G5, G19; fig. 2–5, pl. 3, fig. 10 [early–middle Paleocene (Danian, Selandian), Georgia].
- 2001** *Hafniasphaera septata* (Cookson & Eisenack) Schiøler & Wilson, pl. 3, fig. 46 [Late Cretaceous (late Campanian), France].
- 2003** *Spiniferites (Hafniasphaera) cryptovesiculata* (Hansen) Quattrocchio & Sarjeant, p. 140; fig. 6F [early–middle Paleocene (Danian–Selandian), Chile].
- 2003** *Hafniasphaera* sp. Słodkowska, p. 1075; fig. 2, table 1 [Late Cretaceous (late Maastrichtian), Poland].
- 2004** *Spiniferites (Hafniasphaera) cryptovesiculata* (Hansen) Daners & Guerstein, p. 53; pl. 2, fig. 8 [early Paleocene (Danian), Uruguay].
- 2004** *Spiniferites (Hafniasphaera) fluens* (Hansen) Daners & Guerstein, pl. 2, fig. 9 [early Paleocene (Danian), Uruguay].
- 2004** *Spiniferites (Hafniasphaera) septatus* (Cookson & Eisenack) Daners & Guerstein, pl. 2, fig. 7 [early Paleocene (Danian), Uruguay].
- 2004** *Hafniasphaera* sp. Landman et al., fig. 8H, table 1 [Late Cretaceous (late Maastrichtian), New

- Jersey].
- 2004** *Hafniasphaera* cf. *fluens* (Hansen) Marensi et al., p. 918; fig. 4, fig. 5P, 5Q [Late Cretaceous (late Maastrichtian), Argentina].
- 2005** *Hafniasphaera australis* Guler, p. 425, 427, figs. 5M–T, 6A–E [Late Cretaceous (late Maastrichtian), Argentina].
- 2007** *Hafniasphaera septata* (Cookson & Eisenack) Bankole et al., p. 36, pl. 1, fig. 13, table 1, appendix 1 [late Paleocene (Thanetian)–early Eocene (Ypresian), Nigeria].
- 2007** *Hafniasphaera* sp. Bati & Sancay, p. 256; pl. 7, figs. 1–5, text-figs. 4, 9, appendix 1 [Oligocene (Rupelian–Chattian), Turkey].
- 2007** *Hafniasphaera septata* (Cookson & Eisenack) Edwards, p. C4; fig. C4, pl. C2, fig. 13 [late Paleocene (Thanetian), Pakistan].
- 2009** *Hafniasphaera delicata* Fensome et al., p. 34, 35, pl. 4, figs. l–p [last occurrence, early Eocene (late Ypresian), Scotian Margin].
- 2009** *Hafniasphaera fluens* (Hansen) Sluijs & Brinkhuis, p. 1774; pl. 4, figs. F, G [early Eocene (Ypresian), New Jersey].
- 2009** *Spiniferites* (*Hafniasphaera*) *cryptovesiculata* (Hansen) Quattrocchio, p. 151, 156; pl. 1, fig. 13, text-fig. 3 [early–middle Paleocene (Danian–Selandian), Chile].
- 2010** *Hafniasphaera septata* (Cookson & Eisenack) Sánchez et al., pl. 7, fig. 6 [middle Paleocene (Selandian), Chile].
- 2010** *Hafniasphaera septata* (Cookson & Eisenack) Slimani et al., p. 102; pl. 9, fig. 18, tables 1, 2 [Late Cretaceous (late Maastrichtian)–early Paleocene (early Danian), Morocco].
- 2011** *Hafniasphaera cryptovesiculata* (Hansen) Slimani et al., p. 154, 161; fig. 7j, table 1 [Late Cretaceous (early Maastrichtian), Belgium].
- 2012** *Hafniasphaera septata* (Cookson & Eisenack) Adeonipekun et al., p. 94, 98, 103, 104; pl. 2, fig. 12 [late Paleocene (Thanetian), Nigeria].
- 2012** *Hafniasphaera septata* (Cookson & Eisenack) Kenfack et al., p. 121, 122; fig. 7(4) [Late Cretaceous (Maastrichtian)–Paleocene, Cameroon].
- 2012** *Hafniasphaera septata* (Cookson & Eisenack) Oboh-Ikuenobe et al., p. 70, 79; fig. 3, pl. 1, fig. 23 [early Paleocene (Danian), Missouri].
- 2012** *Hafniasphaera septata* (Cookson & Eisenack) René et al., p. 47, 48, 52; pl. 1, fig. 22 [early Eocene (Ypresian), offshore Ivory Coast].
- 2014** *Hafniasphaera fluens* (Hansen) Dastas et al., p. 13–15, 17, 18; fig. 6v, 6w, table S1 [Late Cretaceous (late Maastrichtian)–middle Paleocene (?Selandian), Missouri].
- 2014** *Hafniasphaera hyalospinosa* (Hansen) Dastas et al., p. 13, 18; fig. 5w, 5x, table S1 [early–middle

- Paleocene (Danian–?Selandian), Missouri].
- 2014** *Hafniasphaera* spp. Kocsis et al., pl. 2, fig. 6 [late Paleocene (Thanetian)–early Eocene (Ypresian), Tunisia].
- 2014** *Hafniasphaera multisphaerus* Price and Pospelova, p. 107, 113–115; pl.1, figs. 1–13; pl. 2, figs. 1–12; pl. 3, figs. 7–9; pl. 4, figs. 4–9; pl. 5, figs. 4–11; text-fig. 3 [late Quaternary, Gulf of California].
- 2015** *Hafniasphaera septata* (Cookson & Eisenack) Açikalin et al., p. 258; fig. 6, pl. 7, fig. 5 [early Paleocene (Danian), Turkey].
- 2015** *Hafniasphaera* spp. Unida & Patruno, fig. 3, pl. 1, fig. 12 [Early Cretaceous (early Aptian), Italy].
- 2015** *Hafniasphaera septata* (Cookson & Eisenack) Yans et al., p. 339; pl. 2, fig. 4, appendix [early Eocene (Ypresian), France].
- 2016** *Hafniasphaera hyalospinosa* (Hansen) Awad & Oboh-Ikuenobe, p. 127, 129; fig. 3, pl. 4 fig. 9 [late Paleocene (early Thanetian), Gulf of Guinea].
- 2016** *Hafniasphaera septata* (Cookson & Eisenack) Awad & Oboh-Ikuenobe, pl. 4 fig. 10 [late Paleocene (early Thanetian), Gulf of Guinea].
- 2016** *Hafniasphaera* cf. *H. septata* (Cookson & Eisenack) de Menezes et al., p. 138, 142; fig. 2, 3, fig. 4G, tables 1, 2a [Late Cretaceous (Maastrichtian)–Paleocene, Brazil, India].
- 2016** *Hafniasphaera* sp. cf. *septata* (Cookson & Eisenack) Okeke & Umeji, p. 111; fig. 17(21) [late Paleocene (Thanetian), Nigeria].
- 2017** *Hafniasphaera septata* (Cookson & Eisenack) Lucas & Ebahili, p. 143, 148; figs. 4, 6, pl. 1, fig. 9 [Late Cretaceous (late Campanian), Nigeria].
- 2017** *Hafniasphaera hyalospinosa* (Hansen) Oboh-Ikuenobe et al., p. 33, 38; fig. 5J, fig. 8 [middle Paleocene (Selandian)–early Eocene (Ypresian), Nigeria].
- 2017** *Hafniasphaera graciosa* (Hansen) Țabără et al., p. 113, 117; fig. 5B, fig. 9 [early Paleocene (early Danian), Romania].
- 2017** *Hafniasphaera cryptovesiculata* (Hansen) Vasilyeva, p. 7; fig. 1, pl. 1, fig. 9 [early Paleocene (Danian), Russia].
- 2017** *Hafniasphaera graciosa* (Hansen) Vasilyeva, fig. 1, pl. 1, fig. 6, [early Paleocene (Danian), Russia].
- 2018** *Hafniasphaera septata* (Cookson & Eisenack) Frieling et al., p. 332; fig. 4, pl. 3L [late Paleocene (early Thanetian), Australia].
- 2018** *Hafniasphaera delicata* (Fensome et al.) McLachlan et al., fig. 3, pl. 8, figs. A, B, appendices A, B [Late Cretaceous (late Campanian), Canada].

- 2018** *Hafniasphaera septata* (Cookson & Eisenack) McLachlan et al., fig. 3, pl. 8, fig. C, appendices A, B [Late Cretaceous (late Campanian), Canada].
- 2018** *Hafniasphaera septata* (Cookson & Eisenack) Premaor et al., p. 21, 43; fig. 8H [?Paleocene, Brasil].
- 2019** *Hafniasphaera australis* (Guler) González Estebenet et al., p. 82, 95; fig. 6G, 6H [Late Cretaceous (late Maastrichtian), Argentina].
- 2019** *Hafniasphaera septata* (Cookson & Eisenack) Guédé et al., p. 754; pl. 3, fig. 5 [early Eocene (early Ypresian), Ivory Coast].
- 2019** *Hafniasphaera fluens* (Hansen), de Oliveira Alves et al., p. 9; pl. 7, fig. D, pl. 9, fig. F [Late Cretaceous (late Maastrichtian)–Paleocene, Brasil].
- 2019** *Hafniasphaera hyalospinosa* (Hansen) Osokpor & Obge, fig. 6(2) [Late Cretaceous (early Maastrichtian)–early Paleocene (Danian), Nigeria].
- 2019** *Hafniasphaera* sp. Osokpor & Obge, fig. 6(1) [Late Cretaceous (early Maastrichtian)–early Paleocene (Danian), Nigeria].
- 2019** *Hafniasphaera fluens* (Hansen) Soliman & Slimani, p. 239, 249; fig. 5J, 5K [early Paleocene (Danian), Egypt].
- 2019** *Hafniasphaera septata* (Cookson & Eisenack) Soliman & Slimani, p. 239, 249; fig. 5H, 5I, fig. 3 [Late Cretaceous (late Maastrichtian)–early Paleocene (early Danian), Egypt].
- 2019** *Hafniasphaera* sp. A, Soliman & Slimani, p. 249; fig. 5F, 5G [Late Cretaceous (late Maastrichtian), Egypt].
- 2019** *Hafniasphaera septata* (Cookson & Eisenack) Steeman et al., pl. 6, figs. 4–9 [Paleocene (Danian–Thanetian), Angola].
- 2019** *Hafniasphaera septata* (Cookson & Eisenack) Vellekoop et al., fig. S2(3–5), tables S1–5 [Late Cretaceous (late Maastrichtian)–early Paleocene (early Danian), New Jersey].
- 2019** *Hafniasphaera graciosa* (Hansen) Vieira & Mahdi, p. 37; fig. 3, pl. 6, figs. 5–7 [early Paleocene (Danian), North Sea].
- 2019** *Hafniasphaera septata* (Cookson & Eisenack) Vieira & Mahdi, p. 30, 31, 34, 35, 37; fig. 3, pl. 6, figs. 1–4 [Paleocene (Danian, Thanetian), North Sea].
- 2020** *Hafniasphaera* sp. Leandro et al., p. 4; figs. 2, 3(4) [Miocene (Langhian), Caribbean Sea].

References

- Abd El-Gawad, E., Abdelghany, O., Lotfy, M.M., Abu Siama, M., Hashem, W., 2010. Basin analysis of the Late Cretaceous sediments in United Arab Emirates. *Aust. J. Basic Appl. Sci.* 4, 3526–3545.
- Abdel-Kireem, M.R., Schrank, E., Samir, A.M., Ibrahim, M.I.A., 1996. Cretaceous palaeoecology, palaeogeography and palaeoclimatology of the northern Western Desert, Egypt. *J. Afr. Earth Sci.* 22, 93–112.
- Açikalin, S., Vellekoop, J., Oçakoğlu, F., Yilmaz, İ.Ö., Smit, J., Altiner, S.T., Goderis, S., Vonhof, H., Speijer, R.P., Woelders, L., Fornaciari, E., Brinkhuis, H., 2015. Geochemical and palaeontological characterization of a new K-Pg Boundary locality from the northern branch of the Neo-Tethys: Mudurnu—Göynük Basin, NW Turkey. *Cret. Res.* 52, 251–267.
- Adeonipekun, P.A., Ehinola, O.A., Yussuph, I.A., Toluh, A., Oyelami, A., 2012. Bio-sequence stratigraphy of Shagamu Quarry outcrop, Benin Basin, southwestern Nigeria. *World Appl. Sci. J.* 18, 91–106.
- Alberti, G., 1961. Zur Kenntnis mesozoischer und alttertiärer Dinoflagellaten und Hystrichosphaerideen von Nord- und Mitteldeutschland sowie einigen anderen europäischen Gebieten. *Palaeontogr. Abteilung A*, 116, 1–58, pls. 1–12 (in German).
- Aleksandrova, G.N., Zaporozhets, N.I., 2008. Palynological characteristics of Upper Cretaceous and Paleogene deposits on the west of the Sambian Peninsula (Kaliningrad region), Part 1. *Stratigr. Geol. Correl.* 16, 295–316.
- Aleksandrova, G.N., Beniamovski, V.N., Vishnevskaya, V.S., Zastrozhnov, A.S., 2012. New data on Upper Cretaceous biostratigraphy of the lower Volga region. *Stratigr. Geol. Correl.* 20, 426–465.
- Allameh, M., Torshizian, H., Habiballahei, N., 2011. Palynology and paleoecology of the Sarcheshmeh Formation in Daddanlou village, southeast Qouchan (Khorasan Razavi). *Sediment. Facies* 4, 64–76.
- Allameh, M., Javanbakht, M., Zhiani Noghani Mashhad, F., 2017. Palynofacies and microfacies of Kalat Formation at Chehel-Kaman Valley section (north east Khorasan Razavi). *Sediment. Facies* 10, 121–142.
- Amano, K., Kurita, H., 2020. A new Paleocene species of *Myonera* (Bivalvia: Cuspidariidae) from eastern Hokkaido, northern Japan. *Nautilus* 134, 51–56.
- Amiri, M., Zarei, E., 2020. Study of water-level fluctuations throughout the deposition of the Gurpi Formation based on palynological data in the west of Dehrolan, south of Ilam. *J. Stratigr. Sedimentol. Res. Univ. Isfahan* 36, 77–96 [in Persian].
- Anthonissen, E.D., 2012. A new miocene biostratigraphy for the northeastern North Atlantic: an integrated foraminiferal, bolboformid, dinoflagellate and diatom zonation. *Newslett. Stratigr.* 45, 281–307.
- Antonescu, E., Alexandrescu, G., 1979. Données préliminaires sur les dinoflagellés des couches de Hangu (Sénonien–Paléocène). *Dari Seama ale Institutului Geol. și Geofiz.* 66, 61–93 (in French).
- Antonescu, E., Foucher, J.-C., Odin, G.S., 2001. Les kystes de dinoflagellés de la carrière de Tercis les Bains (Landes, France). In: Odin, G.S. (Ed.), *The Campanian-Maastrichtian Stage Boundary, Characterization at Tercis Les Bain (France) and Correlation with Europe and Other Continents. Developments in Palaeontology and Stratigraphy*, 19. pp. 235–252 (in French).
- Antonescu, E., Foucher, J.-C., Odin, G.S., Schiøler, P., Siegl-Farkas, A., Wilson, G.J., 2001. Dinoflagellate cysts in the Campanian-Maastrichtian succession of Tercis les Bains (Landes, France), a synthesis. In: Odin, G.S. (Ed.), *The Campanian-Maastrichtian Stage Boundary, Characterization at Tercis Les Bain (France) and Correlation with Europe and Other Continents. Developments in Palaeontology and Stratigraphy*, 19. pp. 253–264.
- Archangelsky, S., 1996. Geología y recursos naturales de la plataforma continental Argentina. *Congr. Geol. Argentino*, 13th Actas 13, 67–72 (in Spanish).
- Athersuch, J., 1987. Ostracod faunas from the Halul, Laffan and Nahr Umr Formations of offshore Abu Dhabi, U.A.E. *J. Micropalaeontol.* 5, 1–10.

- Aurisano, R.W., 1989. Upper Cretaceous dinoflagellate biostratigraphy of the subsurface Atlantic coastal plain of New Jersey and Delaware, U.S.A. *Palynology* 13, 143–179.
- Azema, C., Fauconnier, D., Viaud, J.M., 1981. Microfossils from the Upper Cretaceous of Vendée (France). *Rev. Palaeobot. Palynol.* 35, 237–281.
- Awad, W.K., Oboh-Ikuenobe, F.E., 2016. Early Paleogene dinoflagellate cysts from ODP Hole 959D, Côte d'Ivoire-Ghana Transform Margin, West Africa: New species, biostratigraphy and paleoenvironmental implications. *J. Afr. Earth Sci.* 123, 123–144.
- Backhouse, J., 2006. Albion (Lower Cretaceous) dinoflagellate cyst biostratigraphy of the Lower Gearle Siltstone, southern Carnarvon Basin, Western Australia. *Palynology* 30, 43–68.
- Bankole, S.I., Schrank, E., Erdtmann B.-D., 2007. Palynology of the Paleogene Oshosun Formation in the Dahomey Basin, southwestern Nigeria. *Rev. Esp. Micropaleontol.* 39, 29–44.
- Baraboshkin, E.Y., Guzhikov, A.Y., Aleksandrova, G.N., Fomin, V.A., Pokrovsky, B.G., Grishchenko, V.A., Manikin, A.G., Naumov, E.V., 2020. New sedimentological, magnetostratigraphic, and biostratigraphic data on the Campanian–Maastrichtian of Beshkosh Mountain, southwest Crimea. *Stratigr. Geol. Correl.* 28, 816–858.
- Barreda, V.D., 2002. Palinofloras cenozoicas. In: Haller, M.J. (Ed.), *Geología y Recursos Naturales de Santa Cruz. Rel Atorio Del XV Congreso Geológico Argentino, El Calafate II-12*. pp. 545–567 (in Spanish).
- Barreda, V., Palamarczuk, S., 2000a. Palinomorfos continentales y marinos de la Formación Monte León en su área tipo, provincia de Santa Cruz, Argentina. *Ameghiniana* 37, 3–12 (in Spanish).
- Barreda, V., Palamarczuk, S., 2000b. Estudio palinoestratigráfico del Oligoceno tardío-Mioceno en secciones de la costa patagónica y plataforma continental Argentina. In: Aceñolaza, F.G., Herbst, R. (Eds.), *El Neógeno de Argentina, Serie Correlación Geológica 14*. Magna, San Miguel de Tucumán, Argentina, pp. 103–138 (in Spanish).
- Barreda, V., Palazzesi, L., Marensi, S., 2009. Palynological record of the Paleogene Río Leona Formation (southernmost South America): Stratigraphical and paleoenvironmental implications. *Rev. Palaeobot. Palynol.* 154, 22–33.
- Barss, M.S., Bujak, J.P., Williams, G.L., 1979. Palynological zonation and correlation of sixty-seven wells. *Geol. Surv. Can. Pap.* 78-24, 1–118.
- Batil, Z., Sancay, R.H., 2007. Palynostratigraphy of Rupelian Sediments in the Mus Basin, Eastern Anatolia, Turkey. *Micropaleontology* 53, 249–284.
- Begouen, V., Masure, E., Bellier, J.-P., Debross, E.-J., 1990. Premier inventaire des kystes de dinoflagellés des flyschs néocrétacés de la zone sous-pyrénéenne (France); biostratigraphie comparée et paléobiogéographie. *C. R. l'Acad. Sci. Sér. II*, 1383–1389 (in French).
- Beiranvand, B., Zaghib-Turki, D., Ghasemi-Nejad, E., 2014. Integrated biostratigraphy based on planktonic foraminifera and dinoflagellates across the Cretaceous/Paleogene (K/Pg) transition at the Izeh section (SW Iran). *C. R. Palevol* 13, 235–258.
- Besems, R.E., 1993. Dinoflagellate cyst biostratigraphy of Tertiary and Quaternary deposits of offshore NW Borneo. *Geol. Soc. Malays. Bull.* 33, 65–93.
- Brown, S., Downie, C., 1985. Dinoflagellate cyst stratigraphy of Paleocene to Miocene sediments from the Goban Spur (Sites 548–550, Leg 80). In: Bailey, M.G. (Ed.), *Deep Sea Drilling Project, Initial Reports 80*. U.S. Gov. Printing Office, Washington, pp. 643–651.
- Bujak, J.P., Williams, G.L., 1978. Cretaceous palynostratigraphy of offshore southeastern Canada. *Geol. Surv. Can. Bull.* 297, 1–19.
- Burger, D., 1982. Palynological examination of late Mesozoic sediments in GSQ Hughenden 7, and notes on geological events in the northern Eromanga Basin. *Queensl. Gov. Min. J.* 83, 421–432.
- Bütschli, O., 1885. Erster Band. Protozoa. In: Bronns, H.G. (Ed.), *Die Klassen und Ordnungen des Thier-Reichs, wissenschaftlich dargestellt in Wort und Bild*. C. F. Winter'sche Verlagsbuchhandlung, Leipzig and Heidelberg, pp. 865–1088 (in German).
- Châteauneuf, J.-J., 1980. Palynostratigraphie et paléoclimatologie de l'Eocène Supérieur et de l'Oligocène du Bassin de Paris. *Bur. Rech. Géol. Min., Mém.* 116, 1–360 (in French).

- Colin, J.P., Lehmann, R.A., Morgan, B.E., 1981. Cretaceous and Late Jurassic biostratigraphy of the North Celtic Sea Basin, offshore Southern Ireland. In: Neale, J.W. (Ed.), *Microfossils from recent and fossil shelf seas*. British Micropalaeontological Society, pp. 122–155.
- Cookson, I.C., Eisenack, A., 1958. Microplankton from Australian and New Guinea upper Mesozoic sediments. *Proc. R. Soc. Victoria* 70, 19–78, pls. 1–12.
- Cookson, I.C., Eisenack, A., 1960. Microplankton from Australian Cretaceous sediments. *Micropaleontology* 6, 1–18.
- Cookson, I.C., Eisenack, A., 1962. Additional microplankton from Australian Cretaceous Sediments. *Micropaleontology* 8, 485–507.
- Cookson, I.C., Eisenack, A., 1967. Some microplankton from the Paleocene Rivernook Bed, Victoria. *Proc. R. Soc. Victoria* 80, 247–257, pls. 39–42.
- Corradini, D., 1971. Preliminary reports on the study of non-calcareous microplankton assemblages from the Upper Cretaceous of the northern Apennines. *Proc. 2nd Planktonic Conf. Rome, 1970*, 321–330.
- Corradini, D., 1973. Non-calcareous microplankton from the Upper Cretaceous of the northern Apennines. *Boll. della Soc. Paleontol. Ital.* 11, 119–197, pls. 19–39.
- Damassa, S.P., 1979. Danian dinoflagellates from the Franciscan Complex, Mendocino County, California. *Palynology* 3, 191–207.
- Daners, G., Guerstein, G.R., 2004. Dinoflagelados del Maatrichtiense–Paleógeno em la Formación Gaviotín, Cuencas Punta del Este. *Cuen. Sed. Uru.* 2, 37–70.
- Dastas, N.R., Chamberlain Jr, J.A., Garb, M.P., 2014. Cretaceous–Paleogene dinoflagellate biostratigraphy and the age of the Clayton Formation, southeastern Missouri, USA. *Geosci.* 4, 1–29.
- de Coninck, J., 1975. Microfossiles à paroi organique de l'Ypresien du bassin belge. *Serv. Géol. Belg., Prof. Pap.* 1975–12, 1–151, 22 pls. (in French).
- de Coninck, J., 1980. Organic walled microfossils in the clay of Ieper in the Overijse borehole. *Bull. Soc. Belge Geol.* 89, 201–215.
- de Coninck, J., 1986. Organic walled phytoplankton from the Bartonian and Eo-Oligocene transitional deposits of the Woensdrecht Borehole, southern Netherlands. *Meded. Rijks Geol. Dienst, Nieuwe Ser.* 40, 1–49.
- de Coninck, J., 1999. Phytoplankton à paroi organique et phases transgressives vers la transition Paléocène–Éocène dans la partie méridionale du Bassin de la Mer du Nord. *Bull. Soc. Belge Géol.* 105, 139–169 (in French).
- de Menezes, J.B., Garcia, M.J., Premaor, E., De Oliveira, P.E., Arai, M., Cerruti, Bernardes de Oliveira, M.E., Kavali, P.S., Shivanna, M., 2016. Similarities of the K/Pc dinoflagellate cyst associations between South Atlantic and Indian proto-oceans. *Geol. USP, Sér. Cient., São Paulo* 16, 135–149.
- de Oliveira Alves, M.A., Santos, P.R.S., de Lima Filho, M., 2019. Biostratigraphia do limite Cretáceo–Paleógeno da bacia da Paraíba com base na Palinologia. *Estudos Geol.* 29, 3–24 (in Portuguese).
- De Schepper, S., Head, M.J., 2009. Pliocene and Pleistocene dinoflagellate cyst and acritarch zonation of DSDP Hole 610A, eastern North Atlantic. *Palynology* 33, 179–218.
- de Verteuil, L., 1996. Data report: upper Cenozoic dinoflagellate cysts from the continental slope and rise off New Jersey. In: Mountain, G.S., Miller, K.G., Blum, P., Poag, C.W., Twichell, D.C. (Eds.), *Proc. Ocean Drill. Prog., Sci. Res.* 150, College Station, Texas, pp. 439–454.
- de Verteuil, L., 1997. Palynological delineation and regional correlation of the lower through upper Miocene sequences in the Cape May and Atlantic City boreholes, New Jersey Coastal Plain. In: Miller, K.G., Newell, W., Snyder, S.W. (Eds.), *Proc. Ocean Drill. Prog., Sci. Res.*, 150X, College Station, Texas, pp. 129–145.
- de Verteuil, L., Norris, G., 1996. Miocene dinoflagellate stratigraphy and systematics of Maryland and Virginia. *Micropaleontology* 42, 1–172.
- de Wit, R., 1943. Hystrichosphaeridae uit Limburgse vuursteen. *Verh. van het Geol. Genoot. voor Ned. en Kolonien* 13, 363–392 (in Dutch).
- Deaf, A.S., Harding, I.C., Marshall, J.E.A., 2014. Cretaceous (Albian–?early Santonian) palynology and stratigraphy of the Abu Tunis 1x borehole, northern Western Desert, Egypt. *Palynology* 38, 51–77.

- Deflandre, G., 1935. Considérations biologiques sur les microorganismes d'origine planctonique conservés dans les silex de la craie. Bull. Biol. Fr. Belg. 69, 213–244, pls. 5–9 (in French).
- Deflandre, G., 1937. Microfossiles des silex crétacés. Deuxième partie. Flagellés incertae sedis. Hystrichosphaeridés. Sarcodinés. Organismes divers. Ann. Paléontologie 26, 51–103 (also labelled 3–55), pls. 11–18 (also labelled pls. 8–15) (in French).
- Deflandre, G., 1947a. Sur une nouvelle hystrichosphère des silex crétacés et sur les affinités du genre *Cannosphaeropsis* O. We. C. R. Hebd. Séances Acad. Sci. 224, 1574–1576 (in French).
- Deflandre, G., 1947b. Le problème des hystrichosphères. Inst. Océanographique (Monaco), Bull. 918, 1–23 (in French).
- Drugg, W.S., 1967. Palynology of the upper Moreno Formation (Late Cretaceous–Paleocene) Escarpado Canyon, California. Palaeontogr. Abteilung B 120, 1–71, 9 pls.
- Dybkjær, K., Piasecki, S., 2010. Neogene dinocyst zonation for the eastern North Sea Basin, Denmark. Rev. Palaeobot. Palynol. 161, 1–29.
- Edwards, L.E., 1982. Biostratigraphically important species of *Pentadinium* Gerlach 1961 and a likely ancestor, *Hafniasphaera goodmanii* n. sp., from the Eocene of the Atlantic and Gulf Coastal Plains. Palynology 6, 105–117.
- Edwards, L.E., 2007. Paleocene and Eocene dinocysts from the Salt Range, Punjab, northern Pakistan. In: Warwick, P.D., Wardlaw, B.R. (Eds.), Regional studies of the Potwar Plateau area, northern Pakistan. U.S. Geol. Surv. Bull. 2078-C, C1–C10, pls. C1–C2.
- Edwards, L.E., 1998. Dinoflagellates from the Black Mingo Group (Paleocene) of South Carolina. Trans. Am. Philos. Soc., New Ser. 88, 28–48.
- Edwards, L.E., 2001. Dinocyst biostratigraphy of Tertiary sediments from five cores from Screven and Burke Counties, Georgia. U.S. Geol. Surv., Prof. Pap. 1603–G, G1–G25.
- Edwards, L.E., Goodman, D.K., Witmer, R.J., 1984. Lower Tertiary, (Pamunkey Group), dinoflagellate biostratigraphy, Potomac River area, Virginia and Maryland. In: Frederiksen, N.O., Krafft, K. (Eds.), Cretaceous and Tertiary stratigraphy, paleontology and structure, southwestern Maryland and northeastern Virginia, Am. Assoc. Stratigr. Palynol., Field Trip Volume and Guidebook, pp. 137–152.
- Egger, H., Mohamed, O., Freimoser, M., 2012. Obituary for the Walserberg Series in the Cretaceous of the Eastern Alps (Austria, Germany). Aust. J. Earth Sci. 105, 161–174.
- El-Soughier, M.I., Deaf, A.S., Mahmoud, M.S., 2014. Palynostratigraphy and palaeoenvironmental significance of the Cretaceous palynomorphs in the Qattara Rim-1X well, north Western Desert, Egypt. Arab. J. Geosci. 7, 3051–3068.
- Engel, E.R., 1992. Palynologische Evidenz klimarelevanter Ereignisse in miozänen Sedimenten des Nordatlantiks. Geol. Jahrb. A125, 3–139 (in German).
- Ertuğ, K., Bozdoğan, N., Ediger, V.Ş., 1990. Dinoflagellate cysts from the Maastrichtian-Paleocene boundary, S. E. Anatolia, Turkey. Rev. Esp. Micropaleontol. 22, 183–198.
- Eshet, Y., Hoek, R., Almogi-Labin, A., 1994. A new dinocyst-based biostratigraphic framework for Campanian–Maastrichtian organic rich-carbonate sequences in Israel. Geol. Surv. Isr. Rep. GSI/2/94, p. 24.
- Evitt, W.R., 1961. Observations on the morphology of fossil dinoflagellates. Micropaleontology 7, 385–420.
- Farmani, T., Ghasemi-Nejad, E., Beiranvand, B., Maleki-Porazmiani, S., 2020. Biozonation, paleobathymetry and paleoenvironmental study of the Gurpi Formation in southwestern Iran. Iran. J. Earth Sci. 12, 54–68.
- Fechner, G.G., Jortzig, H., Limberg, A., 1997. Ein neuer Eozän-Nachweis im Süden von Berlin. Brandenburg. Geowiss. Beitr. 1/97, 90–96 (in German).
- Fensome, R.A., Williams, G.L., MacRae, R.A., 2009. Late Cretaceous and Cenozoic fossil dinoflagellates and other palynomorphs from the Scotian Margin, offshore eastern Canada. J. Syst. Palaeontol. 7, 1–79.
- Fensome, R.A., Nøhr-Hansen, H., Williams, G.L., 2016. Cretaceous and Cenozoic dinoflagellate cysts

- and other palynomorphs from the western and eastern margins of the Labrador–Baffin Seaway. *Geol. Surv. Den. Greenl. Bull.* 36, 143 pp.
- Fensome, R.A., Williams, G.L., MacRae, R.A., 2019. The Lentin and Williams index of fossil dinoflagellates 2019 edition. *Am. Assoc. Stratigr. Palynol. Contrib. Ser.* 50, 1173 p.
- Fensome, R.A., Taylor, F.J.R., Norris, G., Sarjeant, W.A.S., Wharton, D.I., Williams, G.L., 1993. A classification of fossil and living dinoflagellates. *Micropaleontol. Spec. Publ.* 7, 1–351.
- Fensome, R.A., Crux, J.A., Gard, I.G., MacRae, R.A., Williams, G.L., Thomas, F.C., Fiorini, F., Wach, G., 2008. The last 100 million years on the Scotian Margin, offshore eastern Canada: an event-stratigraphic scheme emphasizing biostratigraphic data. *Atl. Geol.* 44, 93–126.
- Foucher, J.-C., 1975a. Kystes de dinoflagellés des bassins de Mons et de Paris. In: Robaszynski, F. (Ed.), *Les faciès du Sénonien (Maastricht-Mons-Lille). Quelques aspects de la transgression crétacée. Livret-guide des excursions dans le Crétacé, Groupe Français du Crétacé (Mai 1975)*, pp. 21–26 (in French).
- Foucher, J.-C., 1975b. Dinoflagellés et acritarches des silex crétacés du Bassin de Paris une synthèse stratigraphique. *Ann. Sci. l'Université Reims l'Assoc. Rég. l'étude Rech. Sci.* 13, 8–10, pls. 1–2 (in French).
- Foucher, J.-C., 1976a. Les dinoflagellés des silex et la stratigraphie du Crétacé supérieur français. *Rev. Micropaléontologie* 18, 213–220 (in French).
- Foucher, J.-C., 1976b. Microplancton des silex crétacés du Beauvaisis. *Cah. Micropaléontologie, Cent. Natl. la Rech. Sci.* 2, 3–28, pls. 1–6 (in French).
- Foucher, J.-C., 1979. Distribution stratigraphique des kystes de dinoflagellés et des acritarches dans le Crétacé supérieur du bassin de Paris et de l'Europe septentrionale. *Palaeontogr. Abteilung B* 169, 78–105 (in French).
- Foucher, J.-C., 1983. Distribution des kystes de dinoflagelles dans le Crétacé moyen et supérieur du Bassin de Paris. *Cah. Paléontologie, Nouv. Sér.* 4, 23–41 (in French).
- Foucher, J.-C., Robaszynski, F., 1977. Microplancton des silex du Bassin de Mons (Belgique) (dinoflagellés crétacés et daniens). *Ann. Paleontol.* 63, 19–58 (in French).
- Fraser, T., Bon, J., Samuel, L., 1993. A new dynamic Mesozoic stratigraphy for the West Irian micro-continent, Indonesia and its implications. *Proc. Indones. Pet. Assoc. 22nd Annual Conv. Exhib.* 1, (Jakarta 1993), 708–761.
- Frieling, J., Huurdeman, E.P., Rem, C.C.M., Donders, T.H., Pross, J., Bohaty, S.M., Holdgate, G.R., Gallagher, S.J., McGowran, B., Bijl, P.K., 2018. Identification of the Paleocene–Eocene boundary in coastal strata in the Otway Basin, Victoria, Australia. *J. Micropalaeontol.* 37, 317–339.
- Gamero, J.C., Archangelsky, S., 1981. Palinozonas Neocretácicas y Terciarias de la plataforma continental Argentina en la Cuenca del Colorado. *Rev. Esp. Micropaleontol.* 13, 119–140 (in Spanish).
- Garg, R., Khawaja-Ateequzzaman, Prasad, V., 2006. Significant dinoflagellate cyst biohorizons in the Upper Cretaceous–Palaeocene succession of the Khasi Hills, Meghalaya. *J. Geol. Soc. India* 67, 737–747.
- Gedl, P., 1997. Palynological study of an olistolith from the so-called Sucha Formation, Zawoja IG-1 Borehole (Flysch Carpathians, Poland): Age and palaeoenvironment. *Ann. Soc. Geol. Pol.* 67, 203–215.
- Gedl, P., 2004. Dinoflagellate cyst record of the deep-sea Cretaceous–Tertiary boundary at Uzgruň, Carpathian Mountains, Czech Republic. *Geol. Soc. Lond. Spec. Publ.* 230, 257–273.
- Ghasemi-Nejad, E., Hobbi, M.H., Schiøler, P., 2006. Dinoflagellate and foraminiferal biostratigraphy of the Gurpi Formation (upper Santonian-upper Maastrichtian), Zagros Mountains, Iran. *Cret. Res.* 27, 828–835.
- González Estebenet, M.S., Paolillo, M.A., Guler, M.V., 2019. Marine Cretaceous organi-walled dinoflagellate cysts from the Austral-Magallanes Basin. *Lat. Am. J. Sedimentol. Basin Anal.* 26, 75–98.
- González Estebenet, M.S., Guler, M.V., Pérez Panera, J.P., 2021. Late Maastrichtian to Danian organic-

- walled dinoflagellate cysts and calcareous nannofossils from eastern Austral Basin, Patagonia, Argentina. *Rev. Palaeobot. Palynol.* 285, 104342.
- González, W.B.A., Powars, D.S., Seefelt, E.L., Edwards, L.E., Self-Trail, J.M., Durand, C.T., Schultz, A.P., McLaughlin, P.P., 2012. Preliminary physical stratigraphy, biostratigraphy, and geophysical data of the USGS South Dover Bridge Core, Talbot County, Maryland. U.S. Geol. Surv. Open File Rep. 2012-2018, p. 16.
- Gradstein, F., Bäckström, S., 1996. Cainozoic biostratigraphy and palaeobathymetry, northern North Sea and Haltenbanken. *Nor. Geol. Tidsskr.* 76, 3–32.
- Gradstein, F.M., Williams, G.L., Jenkins, W.A.M., Ascoli, P., 1975. Mesozoic and Cenozoic stratigraphy of the Atlantic continental margin, Eastern Canada. *Can. Soc. Petro. Geol. Mem.* 4, 103–131.
- Guédé, K.É., Slimani, H., Yao, N.J.-P., Chekar, M., Koffi, N.J.-C., M’Hamdi, A., Mouah, R., Digbehi, Z.B., 2019. Late Cretaceous to Early Eocene dinoflagellate cysts from the “12 frères” borehole, Fresco, southwestern Côte d’Ivoire: Biostratigraphy and paleobiogeographic implication. *J. Afr. Earth Sci.* 150, 744–756.
- Guerstein, G.R., 1990. Palinología estratigráfica del Terciario de la Cuenca del Colorado, Republica Argentina Parte III: Estudio sistemático y estadístico de la perforación Puerto Belgrano N.º 20. *Rev. Esp. Micropaleontol.* 22, 459–480 (in Spanish).
- Guerstein, G.R., Quattrocchio, M., 1988. Palinozonas e interpretacion estratigraphica mediante analisis de agrupamiento del Terciario de la Cuenca del Colorado, Republica Argentina. *Seg. Jorn. Geol. Bon.* 2, 27–35 (in Spanish).
- Guerstein, G.R., Quattrocchio, M.E., 1991. Datos paleoambientales basados en el estudio estadístico de las palinofloras de la perforación Nadir N.º 1 (Eoceno-Mioceno) Cuenca del Colorado. *Rev. Asoc. Geol. Arg.* 44, 136–149 (in Spanish).
- Guerstein, G.R., Williams, G.L., Fensome, R.A., 2001. *Cannosphaeropsis quattrocchiaie*, a new species of dinoflagellate cyst from the mid Cenozoic of the Colorado Basin, Argentina. *Micropaleontology* 47, 155–167.
- Guerstein, G.R., Guler, M.V., Casadío, S., 2004. Palynostratigraphy and palaeoenvironments across the Oligocene-Miocene boundary within the Centinela Formation, southwestern Argentina. *Geol. Soc. Lond. Spec. Publ.* 230, 325–343.
- Guerstein, G.R., Quattrocchio, M., Deschamps, C., Ruiz, L., 1995. Cenozoic (Pre-Pliocene) paleoenvironmental trends based on palynomorphs from the Colorado Basin, Argentina. *Asoc. Paleontol. Arg. Publ. Espec. Paleogeno Am. del Sur* 3, 63–73.
- Guler, M.V., Guerstein, G.R., Casadío, S., 2005. New dinoflagellate cyst species from the Calafate Formation (Maastrichtian), Austral Basin, Argentina. *Ameghiniana* 42, 419–428.
- Guler, M.V., Guerstein, G.R., 2002. Bioestratigrafía del Oligoceno-Plioceno temprano de la Cuenca del Colorado (Argentina) basada en quistes de dinoflagelados. *Rev. Esp. Micropaleontol.* 34, 359–371 (in Spanish).
- Guler, M.V., Guerstein, G.R., 2003. Quistes de dinoflagelados (Cladopyxiaceae, Gonyaulacaceae, Goniodomaceae e incierta) del Oligoceno-Plioceno temprano de la Cuenca del Colorado, Argentina. *Rev. Esp. Paleontol.* 18, 23–47 (in Spanish).
- Hansen, J.M., 1977. Dinoflagellate stratigraphy and echinoid distribution in upper Maastrichtian and Danian deposits from Denmark. *Geol. Soc. Den. Bull.* 26, 1–26.
- Hansen, J.M., 1979a. A new dinoflagellate zone at the Maastrichtian/Danian Boundary in Denmark. *Danmarks Geol. Undersøgelse Årb.* 1978, 131–140.
- Hansen, J.M., 1979b. Dinoflagellate zonation around the boundary. In: Birkelund, T., Bromley, R.G. (Eds.), *The Maastrichtian and Danian of Denmark, Cretaceous-Tertiary Boundary Events Symposium II. Proceedings.* University of Copenhagen, Copenhagen, pp. 136–141.
- Harada, K., Matsuoka, K., 1974. Dinoflagellata and acritarcha: An introduction to fossil dinoflagellates and acritarchs. *News Osaka Micropaleontol. Spec. Vol.* 1, 1–60.
- Harding, I.C., 1990. A dinocyst calibration of the European Boreal Barremian. *Palaeontogr. Abteilung B* 218, 1–76.

- Harker, S.D., Sarjeant, W.A.S., Caldwell, W.G.E., 1990. Late Cretaceous (Campanian) organic-walled microplankton from the interior plains of Canada, Wyoming and Texas: biostratigraphy, palaeontology and palaeoenvironmental interpretation. *Palaeontogr. Abteilung B* 219, 243 pp., pls. 1–13.
- Head, M.J., Wrenn, J.H., 1992. A forum on Neogene and Quaternary dinoflagellate cysts. In: Head, M.J., Wrenn, J.H. (Eds.), *Neogene and Quaternary dinoflagellate cysts and acritarchs*. American Association of Stratigraphic Palynologists Foundation, Dallas, pp. 1–31.
- Heilmann-Clausen, C., Costa, L.I., 1989. Dinoflagellate zonation of the uppermost Paleocene? to lower Miocene in the Wursterheide research well, northwest Germany. *Geol. Jahrb.* A111, 431–521.
- Heilmann-Clausen, C., Thomsen, E., 1995. Barremian–Aptian dinoflagellates and calcareous nannofossils in the Ahlum 1 borehole and the Otto Gott clay pit, Sarstedt, Lower Saxony Basin, Germany. *Geol. Jahrb.* A141, 257–365.
- Helby, R., Morgan, R., Partridge, A.D., 2004. Updated Jurassic–Early Cretaceous dinocyst zonation, NWS Australia. *Virtual Cent. Econ. Micropalaeontol. Palynol. Geosci. Aust. Publ.* 2.
- Helenes, J., 1984. Dinoflagellates from Cretaceous to early Tertiary rocks of Sebastian Vizcaino Basin, Baja California, Mexico. *Soc. Econ. Paleon. Mineral. Spec. Pub.* 39, 80–106.
- Herngreen, G.F.W., Eillebrecht, A.T.J.M., Gortemaker, R.E., Remmelts, G., Schuurman, H.A.H.M., Verbeek, J.W., 1996. Upper Cretaceous Chalk Group stratigraphy near the Isle of Texel, the Netherlands (a multidisciplinary approach). *Meded. Rijks Geol. Dienst, Nieuwe Ser.* 56, 1–63.
- Hoek, R.P., Eshet, Y., Almogi-Labin, A., 1996. Dinoflagellate cyst zonation of Campanian–Maastrichtian sequences in Israel. *Micropaleontology* 42, 125–150.
- Hultberg, S.U., 1985. Systematic paleontology. In: Hultberg, S.U. (Ed.), *Dinoflagellate studies of the upper Maastrichtian and Danian in southern Scandinavia* (publ. PhD thesis). University of Stockholm, Stockholm, Sweden, pp. 104–189.
- Hultberg, S.U., 1986. Danian dinoflagellate zonation, the C-T boundary and the stratigraphical position of the fish clay in southern Scandinavia. *J. Micropalaeontol.* 5, 37–47.
- Iakovleva, A.I., Heilmann-Clausen, C., 2020. Early and middle Eocene dinoflagellate cysts from the Aktulagay section, Kazakhstan. *Palynology*, p. 31.
- Jan du Chêne, R., Gorin, G., van Stuijvenberg, J., 1975. Etude géologique et stratigraphique (palynologie et nannoflore calcaire) des Grès des Voirons (Palogène de Haute-Savoie, France). *Géologie Alp.* 51, 51–78 (in French).
- Jan du Chêne, R.E. 1987. Étude systématique des kystes de dinoflagellés de la Formation des Madeleines (Danian du Sénégal). *Cah. Micropaléontologie, Nouv. Série* 2, 147–172, pls. 1–28 (in French).
- Jedavi, S., Ghasemi-Nejad, E., Majidifard, M.R., 2018. New finding on the biostratigraphy and paleoecology of the Farrokhi Formation in northwest of Khur, Central Iran, based on palynomorphs and foraminifera. *J. Stratigr. Sedimentol. Res. Univ. Isfahan* 34, 1–20.
- Jenkins, W.A.M., Ascoli, P., Gradstein, F.M., Jansa, L.F., Williams, G.L., 1974. Stratigraphy of the Amoco Ioe A-1 Puffin B-90 Well, Grand Banks of Newfoundland. *Geol. Surv. Can. Pap.* 74–61, 1–12.
- Kaya, M.Y., Dupont-Nivet, G., Proust, J.-N., Roperch, P., Meijer, N., Frieling, J., Fioroni, C., Altiner, S.Ö., Stoica, M., Aminov, J., Mamtimin, M., Guo, Z., 2020. Cretaceous evolution of the Central Asian proto-Paratethys Sea: tectonic, eustatic and climatic controls. *Tectonics* 39, e2019TC005983.
- Kenfack, P.L., Njike Ngaha, P.R., Ekodeck, G.E., Ngueutchoua, G., 2012. Fossils dinoflagellates from the northern border of the Douala sedimentary sub-basin (south-west Cameroon): Age assessment and paleoecological interpretations. *Geosci.* 2, 117–124.
- King, C., Iakovleva, A., Steurbaut, E., Heilmann-Clausen, C., Ward, D., 2013. The Aktulagay section, west Kazakhstan: a key site for northern mid-latitude Early Eocene stratigraphy. *Stratigraphy* 10, 171–209.
- King, C., Iakovleva, A., Heilmann-Clausen, C., Steurbaut, E., 2018. Ypresian (early Eocene) stratigraphy of the Suvlu-Kaya reference section in the Bakhchisaray area (Crimea). *Newslett. Stratigr.* 51, 167–208.

- Kirsch, K.-H., 1991. Dinoflagellatenzysten aus der Oberkreide des Helvetikums und Nordultrahelvetikums von Oberbayern. *Münchner Geowiss. Abh. A, Geol. Paläontol.* 22, 1–306 (in German).
- Kjellström, G., 1973. Maastrichtian microplankton from the Höllviken Borehole No.1 in Scania, southern Sweden. *Sveriges Geol. Undersökning, Ser. C* 67, 1–59.
- Kocsis, L., Ounis, A., Baumgartner, C., Pirkenseer, C., Harding, I.C., Adatte, T., Chaabani, F., Neili, S.M., 2014. Paleocene–Eocene palaeoenvironmental conditions of the main phosphorite deposits (Chouabine Formation) in the Gafsa Basin, Tunisia. *J. Afr. Earth Sci.* 100, 586–597.
- Köthe, A., 1991. Paleogene dinoflagellates from northwest Germany; biostratigraphy and paleoenvironment. *Geol. Jahrb. A* 118, 3–111.
- Köthe, A., 2007. Cenozoic biostratigraphy from the German North Sea sector (G-11-1 borehole, dinoflagellate cysts, calcareous nannoplankton). *Z. Dt. Ges. Geowiss.* 158, 287–327.
- Köthe, A., Piesker, B., 2007. Stratigraphic distribution of Paleogene and Miocene dinocysts in Germany. *Rev. Paléobiologie, Genève* 26, 1–39.
- Kurita, H., Obuse, A., 1994. Paleogene dinoflagellate cysts and pollen from the Haboro Formation, northern central Hokkaido, Japan, and their chronostratigraphic and paleoenvironmental implications. *J. Geol. Soc. Japan* 100, 292–301.
- Landman, N.H., Johnson, R.O., Edwards, L.E., 2004. Cephalopods from the Cretaceous/Tertiary boundary interval on the Atlantic Coastal Plain, with a description of the highest ammonite zones in North America. Part 2. Northeastern Monmouth County, New Jersey. *Bull. Am. Mus. Nat. Hist.* 287, 1–107.
- Leandro, L.M., Santos, A., Carvalhob, M.deA., Fautha, G., 2020. Middle to late Miocene Caribbean dinoflagellate assemblages and palynofacies (DSDP Leg 15 Site 153). *Mar. Micropaleontol.* 160, 101898.
- Lindemann, E., 1928. Abteilung Peridineae (Dinoflagellatae). In: Engler, A., Prantl, K. (Eds.), *Die natürlichen Pflanzenfamilien nebst ihren Gattungen und wichtigeren Arten insbesondere den Nutzpflanzen. Zweite stark vermehrte und verbesserte Auflage herausgegeben von A. Engler.* 2 Band. Wilhelm Engelmann, Leipzig, pp. 3–104 (in German).
- Louwye, S., 2002. Dinoflagellate cyst biostratigraphy of the upper Miocene Deurne Sands (Diest Formation) of northern Belgium, southern North Sea Basin. *Geol. J.* 37, 55–67.
- Louwye, S., 2005. The early and middle Miocene transgression at the southern border of the North Sea Basin (northern Belgium). *Geol. J.* 40, 441–456.
- Louwye, S., Laga, P., 2008. Dinoflagellate cyst stratigraphy and palaeoenvironment of the marginal marine middle and upper Miocene of the eastern Campine area, northern Belgium (southern North Sea Basin). *Geol. J.* 43, 75–94.
- Louwye, S., de Coninck, J., Verniers, J., 2000. Shallow marine lower and middle Miocene deposits at the southern margin of the North Sea Basin (northern Belgium): Dinoflagellate cyst biostratigraphy and depositional history. *Geol. Mag.* 137, 381–394.
- Louwye, S., Mertens, K.N., Vercauteren, D., 2008b. New dinoflagellate cysts from the Miocene of the Porcupine Basin, offshore southwest Ireland. *Palynology* 32, 131–142.
- Louwye, S., Deckers, J., Verhaegen, J., Adriaens, R., Vandenbergh, N., 2020. A review of the lower and middle Miocene of northern Belgium. *Geol. Belgica* 23, 137–156.
- Louwye, S., Foubert, A., Mertens, K., Van Rooij, D., IODP Expedition 307 Scientific Party, 2008a. Integrated stratigraphy and palaeoecology of the lower and middle Miocene of the Porcupine Basin. *Geol. Mag.* 145, 321–344.
- Lucas, F.A., Ebahili, E.O., 2017. Lithofacies, palynology and paleoenvironmental study of Campanian to late Maastrichtian deposits of Ogbabu-1 well Anambra Basin, south eastern Nigeria. *J. Appl. Sci. Environ. Manage.* 21, 137–153.
- Lund, J.J., Lund-Christensen, J., Strauss, C., 1993. Dinoflagellate cyst biostratigraphy and paleoenvironmental analysis in the Miocene of the RCNNS research well Nieder Ochtenhausen, NW Germany. In: Daber, R. (Ed.), *Festschrift Prof. W. Krutzsch. Museum für Naturkunde Berlin*,

- Berlin, pp. 27–37.
- Manum, S.B., Boulter, M.C., Gunnarsdottir, H., Rangnes, K., Scholze, A., 1989. Eocene to Miocene palynology of the Norwegian Sea (ODP Leg 104). In: Winkler, W.R. (Ed.), *Proc. Ocean Drill. Prog., Sci. Res.* 104, College Station, Texas, pp. 611–662.
- McLachlan, S.M.S. & Pospelova, V., 2021. Dinoflagellate cyst-based paleoenvironmental reconstructions and phytoplankton paleoecology across the Cretaceous–Paleogene (K/Pg) boundary interval, Vancouver Island, British Columbia, Canada. *Cret. Res.*, article 104878.
- McLachlan, S.M.S., Pospelova, V., Hebda, R.J., 2018. Dinoflagellate cysts from the upper Campanian (Upper Cretaceous) of Hornby Island, British Columbia, Canada, with implications for Nanaimo Group biostratigraphy and paleoenvironmental reconstructions. *Mar. Micropaleontol.* 145, 1–20.
- Mao, S., 1989. Dinoflagellata. In: Yichun, H., Mao, S., Peihua, R., Xin, S., Sheping, S., Zhenru, W., Jiayun, Y., Hong, Z. (Eds.), *Quaternary microbiotas and their geological significance from northern Xisha Trench of South China Sea*. China University of Geosciences Press, Wuhan, China, pp. 132–218 (in Chinese).
- Mao, S., Mohr, B.A.R., 1992. Late Cretaceous dinoflagellate cysts (?Santonian–Maestrichtian) from the southern Indian Ocean (Hole 748C). In: Wise, S.W.Jr., Palmer Julson, A.A., Schlich, R., Thomas, E. (Eds.), *Proc. Ocean Drill. Prog., Sci. Res.* 120, College Station, Texas, pp. 307–341.
- Marensi, A., Guler, V., Casadío, Guerstein, R., Papú, O., 2004. Sedimentology and palynology of the Calafate Formation (Maestrichtian), Austral Basin, Southern Patagonia, Argentina. *Cret. Res.* 25, 907–918.
- Marheinecke, U., 1986. Dinoflagellaten des Maestrichtium der Grube Hemmoor (Niedersachsen). *Geol. Jahrb.* A93, 3–93 (in German).
- Marheinecke, U., 1992. Monographie der Dinozysten, Acritarcha und Chlorophyta des Maestrichtium von Hemmoor (Niedersachsen). *Palaeontogr. Abteilung B* 227, 1–173, 30 pls. (in German).
- Masure, E., 1985. Les kystes de dinoflagellés de l’Autoroute A 10. *Cret. Res.* 6, 199–206 (in French).
- May, F.E., 1980. Dinoflagellate cysts of the Gymnodiniaceae, Peridiniaceae, and Gonyaulacaceae from the Upper Cretaceous Monmouth Group, Atlantic Highlands, New Jersey. *Palaeontogr. Abteilung B* 172, 10–116, 23 pls.
- McCarthy, F.M.G., Mudie, P.J., 1996. Palynology and dinoflagellate biostratigraphy of upper cenozoic sediments from sites 898 and 900, Iberia Abyssal Plain. In: Whitmarsh, R.B., Sawyer, D.S., Klaus, A., Masson, D.G. (Eds.), *Proc. Ocean Drill. Prog., Sci. Res.* 149, College Station, Texas, pp. 241–265.
- McMinn, A., 1988. Outline of a Late Cretaceous dinoflagellate zonation of northwestern Australia. *Alcheringa* 12, 137–156.
- Mehrotra, N.C., Venkatachala, B., Swamy, S.N., Kapoor, P.N., 2002. Palynology in hydrocarbon exploration: the Indian scenario. Part I: Category I: Basins. *Mem. Geol. Soc. India* 48, 61–88.
- Mehrotra, N.C., Venkatachala, B.S., Kapoor, P.N., 2010. Palynology in hydrocarbon exploration: High impact palynological studies in western offshore and Krishna-Godavari Basins. *J. Geol. Soc. India* 75, 364–379.
- Mercier, J., 1938. Microplancton due Crétacé supérieur de l’Ouest du Bassin de Paris. Note préliminaire. *Compte rendu Somm. des Séances la Soc. Géol. Fr.* 95–96 (in French).
- Mohamed, O., Piller, W.E., 2017. A model of dinoflagellate cyst distribution around the K/Pg boundary and its paleoenvironmental implications (Eastern Alps). *Aust. J. Earth Sci.* 110, 34–40.
- Mohamed, O., Piller, W.E., Egger, H., 2012. The dinocyst record across the Cretaceous/Palaeogene boundary of a bathyal mid-latitude Tethyan setting: Gosau Group, Gams Basin, Austria. *Cret. Res.* 35, 143–168.
- Mohamed, O., Mahdy, F., Tahoun, S.S., 2019. Dinoflagellate cyst biostratigraphy of the Santonian–Oligocene succession of the Drazia-1 well, north Western Desert, Egypt. *J. Afr. Earth Sci.* 158, 103511.
- Moradian, F., Allameh, M., 2010. Palynology of the Abderaz Formation in Hamam Ghaleh in Kopet Dagh sedimentary basin. 1st Int. Appl. Geol. Congr. Dep. Geol. Islam. Azad Univ. Mashhad

- Branch, Iran, 920–924.
- Morgenroth, P., 1966. Mikrofossilien und Konkretionen des nordwesteuropäischen Untereozäns. *Palaeontogr. Abteilung B* 119, 1–53, pls. 1–11 (in German).
- Moshkovitz, S., Habib, D., 1993. Calcareous nannofossil and dinoflagellate stratigraphy of the Cretaceous-Tertiary boundary, Alabama and Georgia. *Micropaleontology* 39, 167–191.
- Mountain, G.S., Miller, K.G., Blum, P., Alm, P.-G., Aubry, M.-P., Burkle, L.H., Christensen, B.A., Compton, J., Damuth, J.E., DeConinck, J.-F., De Verteuil, L., Fulthorpe, C.S., Gartner, S., Guérin, G., Hesselbo, S.P., Hoppie, B., Katz, M.E., Kotake, N., Lorenzo, J.M., McCracken, S., McHugh, C.H., Quayle, W.C., Saito, Y., Snyder, S.W., Ten Kate, W.G., Urbat, M., Van Fossen, M.C., Vecsei, A., 1994. New Jersey continental slope and rise. In: Maddox, E.M. (Ed.), *Proc. Ocean Drill. Prog., Init. Rep.* 150, College Station, Texas, p. 885, 2 pls.
- Munsterman, D.K., Brinkhuis, H., 2004. A southern North Sea Miocene dinoflagellate cyst zonation. *Geol. Mijnb.* 83, 267–285.
- Munsterman, D.K., ten Veen, J.H., Menkovic, A., Deckers, J., Witmans, N., Verhaegen, J., Kerstholt-Boegehold, S.J., van de Ven, T., Busschers, F.S., 2019. An updated and revised stratigraphic framework for the Miocene and earliest Pliocene strata of the Roer Valley Graben and adjacent blocks. *Geol. Mijnb.* 98, Article e8.
- Musacchio, E.A., Vallati, P., Simeoni, M., 2007. Marine microfossil assemblages from Miocene sedimentary cycles in San Jorge Gulf Basin, Chubut, Argentina. In: Díaz-Martínez, E., Rábano, I. (Eds.), 4th Eur. Meet. *Palaeontol. Stratigr. Lat. Am. Cuad. del Mus. Geomin.* 8, 279–283.
- Nøhr-Hansen, H., Williams, G.L., Fensome, R.A., 2016. Biostratigraphic correlation of the western and eastern margins of the Labrador–Baffin Seaway and implications for the regional geology. *Geol. Surv. Den. Greenl. Bull.* 37, 1–74.
- Oboh-Ikuenobe, F.E., Antolinez-Delgado, H., Awad, W.K., 2017. Dinoflagellate cyst assemblages, biostratigraphy and paleoenvironment of a Paleocene–early Eocene sedimentary succession in the northern Niger Delta Basin: Comparison with low, mid and high latitude regions. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 481, 29–43.
- Okeke, K.K., Umeji, O.P., 2016. Palynostratigraphy, palynofacies and palaeoenvironment of deposition of Selandian to Aquitanian sediments, southeastern Nigeria. *J. Afr. Earth Sci.* 120, 102–124.
- Oloto, I.N., 1990. Palynological assemblage from the Danian of South-West Nigeria. *Acta Palaeobot.* 30, 23–30.
- Oloto, I.N., 1992. Succession of palynomorphs from the early Eocene of Gbekebo-1 well in S.W. Nigeria. *J. Afr. Earth Sci.* 15, 441–452.
- Olszewska-Nejbert, D., Barski, M., 2007. Uwagi o wieku utworów paleogeńskich na podstawie cyst dinoflagellat w Mielniku (wschodnia Polska). XX *Konf. Nauk. Paleobiol. i Biostratygrafów PTG*, Św. Katarzyna Pod Łysicą, 10–13 września 2007. 99–100 (in Polish).
- Osokpor, J., Ogbe, O.B., 2019. Sequence stratigraphic signatures from Xen-1 well: key for understanding Cretaceous–Tertiary transitional events in the northwestern Niger Delta Basin, Nigeria. *Pet. Coal* 61, 860–879.
- Palamarczuk, S., Barreda, V., 1998. Bioestratigrafía en base a quistes de dinoflagelados de la Formación Chenque (Mioceno), provincia del Chubut, Argentina. *Ameghiniana* 35, 415–426 (in Spanish).
- Palynodata Inc., White, J.M., 2008. Palynodata Datafile: 2006 version, with introduction by J. M. White. *Geol. Surv. Can. Open File* 5793.
- Paredes, J.M., Foix, N., Guerstein, G.R., Guler, M.V., Irigoyen, M., Moscoso, P., Giordano, S., 2015. A late Eocene-early Oligocene transgressive event in the Golfo San Jorge Basin: Palynological results and stratigraphic implications. *J. South Am. Earth Sci.* 63, 293–309.
- Parras, A., Guerstein, G.R., Pérez Panera, J.P., Griffin, M., Nández, C., Cusminsky, G., Quiroga, A., 2020. Integrated stratigraphy and paleontology of the lower Miocene Monte León Formation, southeastern Patagonia, Argentina: Unraveling paleoenvironmental changes and factors controlling sedimentation. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 556, 109701.
- Pascher, A., 1914. Über flagellaten und algen. *Dtsch. Bot. Gesellschaft, Berichte* 32, 136–160.

- Pastiels, A., 1948. Contributions à l'étude des microfossiles de l'Eocène belge. Musée R. d'histoire Nat. Belg., Mém. 109, 3–77 (in French).
- Pavlishina, P., 1995. Maastrichtian dinoflagellate cysts from North Bulgaria—taxonomy, biostratigraphical and palaeoenvironmental interpretations. *Geol. Balc.* 25, 125–143.
- Pavlishina, P., Verreussel, R., Leereveld, H., Summesberger, H., Wagreeich, M., 2004. Palynological study of Gosau Group deposits (Upper Cretaceous) of the Northern Calcareous Alps (Austria). *Ann. des Naturhist. Mus. Wien* 106A, 67–90.
- Pearce, M.A., Jarvis, I., Ball, P.J., Laurin, J., 2020. Palynology of the Cenomanian to lowermost Campanian (Upper Cretaceous) Chalk of the Trunch Borehole (Norfolk, UK) and a new dinoflagellate cyst bioevent stratigraphy for NW Europe. *Rev. Palaeobot. Palynol.* 278, 104188.
- Pervushov, E.M., Seltser, V.B., Benyamovskiy, V.N., Aleksandrova, G.N., Kalyakin, E.A., Vishnevskaya, V.S., Kopaevich, L.F., Akhlestina, E.F., Ovechkina, M.N., 2015. Biostratigraphic subdivision of Kokurino section (Saratov region) and some aspects of Campanian stratigraphy in Middle Volga. *Bull. Moscow Inst. Appl. Math.* 2, 51–84 (in Russian).
- Piasecki, S., 2003. Neogene dinoflagellate cysts from Davis Strait, offshore West Greenland. *Mar. Pet. Geol.* 20, 1075–1088.
- Powell, A.J., 1986. Latest Palaeogene and Earliest Neogene dinoflagellate cysts from the Lemme section, Northwest Italy. *Am. Assoc. Stratigr. Palynol. Contrib. Ser.* 17, 83–104.
- Powell, A.J., 1992. Dinoflagellate cysts of the Tertiary system. In: Powell, A.J. (Ed.), *A stratigraphic index of dinoflagellate cysts*. Br. Micropalaeontol. Soc., Spec. Pub. Ser., Chapman and Hall, London, pp. 155–229, pls. 4.1–4.11.
- Premaor, E., Souza, P.A., Ferreira, E.P., Guerstein, G.R., Arai, M., 2018. Palinotaxonomia da seção Cretácea a Neogena da Bacia de Pelotas, Brasil: cistos de dinoflagelados das ordens Ptychodiscales e Gonyaulacales. *Pesqui. em Geociências* 45, e647 (in Portuguese).
- Price, A.M., Pospelova, V., 2014. *Spiniferites multisphaerus*, a new dinoflagellate cyst from the Late Quaternary of the Guaymas Basin, Gulf of California, Mexico. *Palynology* 38, 101–116.
- Prince, I.M., Jarvis, I., Tocher, B.A., 1999. High-resolution dinoflagellate cyst biostratigraphy of the Santonian–basal Campanian (Upper Cretaceous): new data from Whitecliff, Isle of Wight, England. *Rev. Palaeobot. Palynol.* 105, 143–169.
- Quaijtaal, W., Donders, T.H., Persico, D., Louwye, S., 2014. Characterising the middle Miocene Mi-events in the Eastern North Atlantic realm: A first high-resolution marine palynological record from the Porcupine Basin. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 399, 140–159.
- Quattrocchio, M.E., 2009. Paleogene dinoflagellate cysts from Punta Prat, southern Chile. *Palynology* 33, 141–156.
- Quattrocchio, M.E., Sarjeant, W.A.S., 2003. Dinoflagellates from the Chorrillo Chico Formation (Paleocene) of southern Chile. *Ameghiniana* 40, 129–153.
- Rabbani, J., Ghasemi-Nejad, E., Amini, A.A.H., 2009. Palynostratigraphy and sequence stratigraphy of the Gurpi Formation in Darreh-Shahr section, southeast of Ilam. *Iran. J. Geol.* 3, 3–13 (in Persian).
- Rabbani, J., Ghasemi-Nejad, E., Ashoir, A., Vahidinia, M., 2015. Quantitative palynostratigraphy and palaeoecology of Tethyan Paleocene–Eocene red beds in north of Zagros sedimentary basin, Iran. *Arab. J. Geosci.* 8, 827–838.
- Rademakers, P.C.M., 1987. *Cannosphaeropsis utinensis* in Limburg vuursteen. *Grondboor en Hamer* 41, 71–72 (in Dutch).
- Rademakers, P.C.M., 1995. Hystrichosphaeridae in de vuursteenhorizonten van de Kalksteen van Lanaye (Formatie van Gulpen) van het Maastrichtien in Zuid-Limburg en aangrenzend Belgisch gebied. *Grondboor en Hamer* 49, 130–139.
- Radmacher, W., Pérez-Rodríguez, I., Arz, J.A., Pearce, M.A., 2014. Dinoflagellate biostratigraphy at the Campanian–Maastrichtian boundary in Zumaia, northern Spain. *Cret. Res.* 51, 309–320.
- Radmacher, W., Mangerud, G., Tyszka, J., 2015. Dinoflagellate cyst biostratigraphy of Upper Cretaceous strata from two wells in the Norwegian Sea. *Rev. Palaeobot. Palynol.* 216, 18–32.
- Radmacher, W., Kobos, K., Tyszka, J., Jarzynka, A., Arz, J.A., 2020. Palynological indicators of

- palaeoenvironmental perturbations in the Basque-Cantabrian Basin during the latest Cretaceous (Zumaia, northern Spain). *Mar. Pet. Geol.* 112, 104107.
- Rasmussen, E.S., Dybkjær, K., Piasecki, S., 2010. Lithostratigraphy of the upper Oligocene–Miocene succession of Denmark. *Geol. Surv. Den. Greenl. Bull.* 22, 1–92.
- Rauscher, R., Doubinger, J., 1982. Les dinokystes du Maestrichtien phosphaté au Maroc. *Sci. Géol. Bull.* 35, 97–116 (in French).
- Reich, M., Frenzel, P., 2002. Die fauna und flora der Rügener Schreibkreide (Maestrichtium, Ostsee). *Arch. Geschiebekd.* 3, 73–284 (in German).
- René, B.G., Bruno, D.Z., Raphael, Y.K., 2012. Stratigraphie palynologique du Maestrichtien supérieur–Eocène supérieur du bassin sédimentaire offshore de Côte d’Ivoire, Afrique de l’Ouest. *Int. J. Afr. Stud.* 6, 40–57.
- Riding, J.B., Davey, R.J., 1989. *Rotosphaeropsis thula* (Davey 1982) comb. nov., emend.: a dinoflagellate cyst from the Upper Jurassic–Lower Cretaceous of England. *J. Micropalaeontol.* 8, 109–112.
- Riding, J.B., Helby, R.J., 2001. Some stratigraphically significant dinoflagellate cysts from the Early Cretaceous (Aptian and Albian) of Australia. *Mem. Assoc. Aust. Palaeontol.* 24, 225–235.
- Riding, J.B., Kyffin-Hughes, J.E., 2004. A review of the laboratory preparation of palynomorphs with a description of an effective non-acid technique. *Rev. Bras. Paleontol.* 7, 13–44.
- Riding, J.B., Moorlock, B.S.P., Jeffery, D.H., Hamblin, R.J.O., 1997. Reworked and indigenous palynomorphs from the Norwich Crag Formation (Pleistocene) of eastern Suffolk: implications for provenance, palaeogeography and climate. *Proc. Geol. Assoc.* 108, 25–38.
- Riegel, W., 1974. New forms of organic-walled microplankton from an Upper Cretaceous assemblage in Southern Spain. *Rev. Esp. Micropaleontol.* 6, 347–366.
- Robaszynski, F., Bless, M.J.M., Felder, P.J., Foucher, J.-C., Legoux, O., Manivit, H., Meesen, J.P.M.T., Van der Tuuk, L.A., 1985. The Campanian–Maestrichtian boundary in the chalky facies close to the type–Maestrichtian area. *Bull. Centres Rech. Explor. Elf-Aquitaine* 9, 1–113.
- Robinson, A.G., Banks, C.J., Rutherford, M.M., Hirst, J.P.P., 1995. Stratigraphic and structural development of the Eastern Pontides, Turkey. *J. Geol. Soc. Lond.* 152, 861–872.
- Roncaglia, L., 2002. Lower Maestrichtian dinoflagellates from the Viano Clay Formation at Viano, northern Apennines, Italy. *Cret. Res.* 23, 65–76.
- Roncaglia, L., Corradini, D., 1997a. Correlation of key dinoflagellate events with calcareous nannoplankton and planktonic foraminiferal zones in the Solignano Formation (Maestrichtian, Late Cretaceous), northern Apennines, Italy. *Rev. Palaeobot. Palynol.* 97, 177–196.
- Roncaglia, L., Corradini, D., 1997b. Upper Campanian to Maestrichtian dinoflagellate zonation in the northern Apennines, Italy. *Newslett. Stratigr.* 35, 29–57, pls. 1–2.
- Sánchez, A., Pavlishina, P., Godoy, E., Hervé, F., Fanning, C.M., 2010. On the presence of upper Paleocene rocks in the foreland succession at Cabo Nariz, Tierra del Fuego, Chile: geology and new palynological and U–Pb data. *Andean Geol.* 37, 413–432.
- Santos, A., Helenes, J., Carvalho, M. de A., 2019. Late Cretaceous (early Turonian) dinoflagellate cysts from the Sergipe Basin, northeastern Brazil. *Palynology* 43, 151–173.
- Sarjeant, W.A.S., 1985. A restudy of some dinoflagellate cyst holotypes in the University of Kiel collections: VI. Late Cretaceous dinoflagellate cysts and other palynomorphs in the Otto Wetzel collection. *Meyniana* 37, 129–185.
- Sarjeant, W.A.S., 1986. A restudy of Pastiels’ (1948) dinoflagellate cysts from the Early Eocene of Belgium. *Bull. l’Institut R. des Sci. Nat. Belgique Sci. la Terre* 59, 5–43.
- Schiøler, P., 2005. Dinoflagellate cysts and acritarchs from the Oligocene–Lower Miocene interval of the Alma-1X well, Danish North Sea. *J. Micropalaeontol.* 24, 1–37.
- Schiøler, P., Wilson, G.J., 1993. Maestrichtian dinoflagellate zonation in the Dan Field, Danish North Sea. *Rev. Palaeobot. Palynol.* 78, 321–351.
- Schiøler, P., Wilson, G.J., 2001. Dinoflagellate biostratigraphy around the Campanian–Maestrichtian boundary at Tercis le s Bains, southwest France. In: Odin, G.S. (Ed.), *The Campanian–Maestrichtian*

- stage boundary, characterization at Tercis les Bain (France) and correlation with Europe and other continents. 19. *Dev. Palaeontol. Strat.* pp. 221–234.
- Schiøler, P., Brinkhuis, H., Roncaglia, L., Wilson, G.J., 1997. Dinoflagellate biostratigraphy and sequence stratigraphy of the Type Maastrichtian (Upper Cretaceous), ENCI Quarry, The Netherlands. *Mar. Micropaleontol.* 31, 65–95.
- Schiøler, P., Andsbjerg, J., Clausen, O.R., Dam, G., Dybkjær, K., Hamberg, L., Heilmann-Clausen, C., Johannessen, E.P., Kristensen, L.E., Prince, I., Rasmussen, J.A., 2007. Lithostratigraphy of the Palaeogene–lower Neogene succession of the Danish North Sea. *Geol. Surv. Den. Greenl. Bull.* 12, 1–77.
- Schrank, E., 1984. Organic-geochemical and palynological studies of a Dakhla Shale profile (Late Cretaceous) in southeast Egypt. Part A: Succession of microfloras and depositional environment. *Berliner Geowiss. Abh. A* 50, 189–207.
- Schrank, E., 1987. Palaeozoic and Mesozoic palynomorphs from northeast Africa (Egypt and Sudan) with special reference to pollen and dinoflagellates. *Berliner Geowiss. Abh. A* 75, 249–310.
- Schrank, E., 1988. Effects of chemical processing on the preservation of peridinioid dinoflagellates: A case from the Late Cretaceous of NE Africa. *Rev. Palaeobot. Palynol.* 56, 123–140.
- Schrank, E., Perch-Nielsen, K., 1985. Late Cretaceous palynostratigraphy in Egypt with comments on Maastrichtian and early Tertiary calcareous nannofossils. *Newslett. Stratigr.* 15, 81–99.
- Schumacker-Lambry, J., 1977. Microfossiles végétaux ?planctoniques. In: Streel, M., Bick, H., Fairon-Demaret, M., Schumacker-Lambry, J., Vanguetaine, M. (Eds), *Macro- et microfossiles végétaux dans le contexte litho- et biostratigraphique du Senonien–Paléocène de la rive gauche de la Meuse au nord de Liège, Belgique. Livret-guide de l'excursion du 22 septembre 1977 à l'occasion du symposium 'Apport des techniques récentes en Palynologie'*. Université de Liège, Liège, pp. 49–53, pls. 1–7 (in French).
- Schumacker-Lambry, J., 1978. Palynologie du Landénien inférieur (Paléocène) à Gelinden-Overbroek/Belgique. Relations entre les microfossiles et le sédiment, Laboratoire de Paléobotanique et de Paléopalynologie. Liège, Belgium, p. 157, 13 pls. (in French).
- Schumacker-Lambry, J., Chateauneuf, J.-J., 1976. Dinoflagellés et acritarches des marnes Heersiennes de Gelinden (base du Landénien, Paléocène, Belgique). *Rev. Paleobotany Palynol.* 21, 267–294 (in French).
- Senemari, S., 2012. Nannostratigraphy of Gurpi Formation in southeast of Shiraz. *Sediment. Facies* 5, 75–84 (in Persian).
- Sheldon, E., Gravesen, P., Nøhr-Hansen, H., 2012. Geology of the Femern Bælt area between Denmark and Germany. *Geol. Surv. Den. Greenl. Bull.* 26, 13–16.
- Siegl-Farkas, A., 1997. Dinoflagellate stratigraphy of the Senonian formations of the Transdanubian Range. *Acta Geol. Hungarica* 40, 73–100.
- Siegl-Farkas, Á., Wagreich, M., 1996. Age and palaeoenvironment of the spherulite-bearing polányi Marl Formation (Upper Cretaceous, Hungary) on basis of palynological and nannoplankton investigation. *Acta Biol. Szeged.* 41, 23–36.
- Slimani, H., 2000. Nouvelle zonation aux kystes de dinoflagellés du Campanien au Danien dans le nord et l'est de la Belgique et dans le sud-est des Pays-Bas. *Mem. Geol. Surv. Belg.* 46, 1–88.
- Slimani, H., 2001. Les kystes de dinoflagellés du Campanien au Danien dans la région de Maastricht (Belgique, Pays-Bas) et de Turnhout (Belgique): biozonation et corrélation avec d'autres régions en Europe occidentale. *Geol. Palaeontol.* 35, 161–201 (in French).
- Slimani, H., Louwye, S., Toufiq, A., 2010. Dinoflagellate cysts from the Cretaceous–Paleogene boundary at Ouled Haddou, southeastern Rif, Morocco: biostratigraphy, paleoenvironments and paleobiogeography. *Palynology* 34, 90–124.
- Slimani, H., Louwye, S., Duser, M., Lagrou, D., 2011. Connecting the Chalk Group of the Campine Basin to the dinoflagellate cyst biostratigraphy of the Campanian to Danian in borehole Meer (northern Belgium). *Geol. Mijnb.* 90, 129–164.
- Slimani, H., Benam, V.M., Țabără, D., Habiba, A., Jbari, H., Chekar, M., Mahboub, I., M'Hamdi, A.,

- 2021a. Distribution of dinoflagellate cyst assemblages and palynofacies in the Upper Cretaceous deposits from the neritic Bou Lila section, External Rif (northwestern Morocco): Implications for the age, biostratigraphic correlations and paleoenvironmental reconstructions. *Mar. Micropaleontol.* 162, 101951.
- Slimani, H., M'Hamdi, A., Uchman, A., Gasiński, M.A., Guédé, K.É., Mahboub, I. 2021b. Dinoflagellate cyst biostratigraphy of Upper Cretaceous turbiditic deposits from a part of the Bąkowiec section in the Skole Nappe (Outer Carpathians, southern Poland). *Cret. Res.* 123, 104780.
- Słodkowska, B., 2003. Wstępne dane o badaniach fitoplanktonu w Kamiennym Dole (okolice Kazimierza Dolnego). *Prz. Geol.* 51, 1075–1078.
- Sluijs, A., Brinkhuis, H., 2009. A dynamic climate and ecosystem state during the Paleocene-Eocene Thermal Maximum: inferences from dinoflagellate cyst assemblages at the New Jersey Shelf. *Biogeosciences* 6, 5163–5215.
- Smelror, M., Key, R.M., Smith, R.A., Njange, F., 2008. Late Jurassic and Cretaceous palynostratigraphy of the onshore Rovuma Basin, northern Mozambique. *Palynology* 32, 63–76.
- Soliman, A., Slimani, H., 2019. The Cretaceous–Paleogene (K/Pg) boundary in the Dababiya Borehole, southern Egypt: An organic-walled dinoflagellate cyst approach. *Cret. Res.* 98, 230–249.
- Soliman, A., Suttner, T.J., Lukeneder, A., Summesberger, H., 2009. Dinoflagellate cysts and ammonoids from Upper Cretaceous sediments of the Pemberger Formation (Krappfeld, Carinthia, Austria). *Ann. des Naturhist. Mus. Wien*, 110A, 401–421.
- Soncini, M.-J., Rauscher, R., 1986. Associations de dinokystes du Maastrichtien–Paléocène phosphaté au Maroc. *Bull. Centres Rech. Explor. Elf-Aquitaine* 12, 427–450, 4 pls. (in French).
- Srivastava, S.K., 1995. Dinocyst biostratigraphy of Santonian–Maestrichtian formations of the western Gulf Coastal Plain, southern United States. *Palaeobot.* 42, 249–362.
- Steeman, T., De Weirtdt, J., Smith, T., De Putter, T., Mees, F., Louwye, S., 2020. Dinoflagellate cyst biostratigraphy and palaeoecology of the early Paleogene Landana reference section, Cabinda Province, Angola. *Palynology* 44, 280–309.
- Steinkraus, W., 1978. Biostratigraphy. In: Amato, R.V., Bebout, J.W. (Eds.), Geological and operational summary, COST No. GE-1 well, Southeast Georgia Embayment area, South Atlantic OCS, U.S. Geol. Surv. Open File Rep. 78-668. pp. 29–41.
- Strauss, C., Lund, J.J., Lund-christensen, J., 2001. Miocene dinoflagellate cyst biostratigraphy of the Nieder Ochtenhausen research borehole (NW Germany). *Geol. Jahrb.* A152, 395–447.
- Surlyk, F., Rasmussen, S.L., Boussaha, M., Schiøler, P., Schovsbo, N.H., Sheldon, E., Stemmerik, L., Thibault, N., 2013. Upper Campanian–Maestrichtian holostratigraphy of the eastern Danish Basin. *Cret. Res.* 46, 232–256.
- Țabără, D., Slimani, H., 2017. Dinoflagellate cysts and palynofacies across the Cretaceous-Paleogene boundary interval of the Vrancea Nappe (Eastern Carpathians, Romania). *Geol. Q.* 61, 39–52.
- Țabără, D., Slimani, H., Mare, S., Chira, C.M., 2017. Integrated biostratigraphy and palaeoenvironmental interpretation of the Upper Cretaceous to Paleocene succession in the northern Moldavidian Domain (Eastern Carpathians, Romania). *Cret. Res.* 77, 102–123.
- Taylor, F.J.R., 1980. On dinoflagellate evolution. *BioSystems* 13, 65–108.
- Thomsen, E., Heilmann-Clausen, C., 1985. The Danian-Selandian boundary at Svejstrup with remarks on the biostratigraphy of the boundary in western Denmark. *Geol. Soc. Den. Bull.* 33, 341–362.
- Tocher, B.A., 1987. Campanian to Maestrichtian dinoflagellate cysts from the United States Atlantic Margin, Deep Sea Drilling Project, Site 612. In: Turner, K.L. (Ed.), Deep Sea Drilling Project, Initial Reports 95, U.S. Gov. Printing Office, Washington, pp. 419–428.
- Torricelli, S., Amore, M.R., 2003. Dinoflagellate cysts and calcareous nannofossils from the upper Cretaceous Saraceno Formation (Calabria, Italy): Implications about the history of the Liguride Complex. *Riv. Ital. Paleontol. Stratigr.* 109, 499–516.
- Unida, S., Patruno, S., 2015. The palynostratigraphy of the upper Maiolica, Selli Level and the lower Marne a Fucoidi units in the proposed Barremian/Aptian (Lower Cretaceous) GSSP stratotype at Gorgo a Cerbara, Umbria–Marche Basin, Italy. *Palynology* 40, 230–246.

- Upshaw, C.F., Armstrong, W.E., Creath, W.B., Kidson, E.J., Sanderson, G.A., 1974. Biostratigraphic framework of Grand Banks. *Am. Assoc. Pet. Geol. Bull.* 58, 1124–1132.
- Vandenbergh, N., Laga, P., Louwye, S., Vanhoorne, R., Marguet, R., De Meuter, F., Wouters, K., Hagemann, H.W., 2005. Stratigraphic interpretation of the Neogene marine – continental record in the Maaseik well (49W0220) in the Roer Valley Graben, NE Belgium. *Mem. Geol. Surv. Belg.* 52, 1–39.
- Vasilyeva, O.N., 2017. Dinocysts of the Belogorodny Formation (Saratov Volga Region). *Yearbook 2016 (Stratigr., Paleontol.)*, Zavaritsky Inst. Geol. Geochem., Ural Branch, Russ. Acad. Sci. 164, 3–8 (in Russian).
- Vellekoop, J., Woelders, L., Sluijs, A., Miller, K.G., Speijer, R.P., 2019. Phytoplankton community disruption caused by latest Cretaceous global warming. *Biogeoscience* 16, 1–19.
- Vieira, M., Mahdi, S., 2019. New Paleocene species and biostratigraphic relevance of the genus *Spiniferites* across the North Sea and Norwegian Sea. *Rev. Palaeobot. Palynol.* 262, 28–43.
- Waterhouse, H.K., 1998. Palynological fluorescence in hinterland reconstruction of a cyclic shallowing-up sequence, Pliocene, Papua New Guinea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 139, 59–82.
- Weems, R.E., Edwards, L.E., Landacre, B.D., 2017. Geology and biostratigraphy of the Potomac River cliffs at Stratford Hall, Westmoreland County, Virginia. In: Hailey, C.M., Jaye, S. (Eds.), *From the Blue Ridge to the beach: Geological field excursions across Virginia*. *Geol. Soc. Am. Field Guide* 47, pp. 125–152.
- Wetzel, O., 1932. Die Typen der baltischen Geschiebef Feuersteine, beurteilt nach ihrem Gehalt an Mikrofossilien. *Z. Geschiebeforsch.* 8, 129–146, pl. 1–3 (in German).
- Wetzel, O., 1933. Die in organischer Substanz Erhaltenen Mikrofossilien des baltischen Kreide-Feuersteins mit einem sediment-petrographischen und stratigraphischen Anhang. *Palaeontogr. Abteilung A* 78, 1–110, pls. 1–4 (in German).
- Wetzel, O., 1940. Mikropaläontologische Untersuchungen an der obersenioren Kreide von Stevns Klint-Kridtbrud auf der dänischen Insel Seeland und an ihrem Feuerstein in geschiebekundlicher Hinsicht. *Z. Geschiebeforsch.* 16, 118–165 (in German).
- Wetzel, O., 1953. Übersicht über die im Feuerstein erhaltenen Protisten der baltischen Kreide. *Paläont. Z.* 27, 37–46 (in German).
- Wetzel, O., 1957. Fossil “microforaminifera” in various sediments and their reaction to acid treatment. *Micropaleontology* 3, 61–64.
- Wetzel, O., 1961. New microfossils from Baltic Cretaceous flintstones. *Micropaleontology* 7, 337–350.
- Wheeler, J.W., Sarjeant, W.A.S., 1990. Jurassic and Cretaceous palynomorphs from the central Alborz Mountains, Iran: Their significance in biostratigraphy and palaeogeography. *Mod. Geol.* 14, 267–374.
- Williams, G.L., 1975a. Plates illustrating Cretaceous species. *Am. Assoc. Stratigr. Palynol. Contrib. Ser.* 4, 65–72.
- Williams, G.L., 1975b. Dinoflagellate and spore stratigraphy of the Mesozoic–Cenozoic, offshore eastern Canada. *Geol. Surv. Can. Pap.* 74-30, Vol. 2, 107–161.
- Williams, G.L., 2006. Palynological analysis of Pan American-Imperial Grand Falls H-09, Whale Basin, Grand Banks of Newfoundland. *Geol. Surv. Can. Open File* 4975, p. 16.
- Williams, G.L., Downie, C., 1966. Further dinoflagellate cysts from the London Clay. In: Davey, R.J., Downie, C., Sarjeant, W.A.S., Williams, G.L. (Eds.), *Studies on Mesozoic and Cainozoic dinoflagellate cysts*. *Bull. Br. Mus. Nat. Hist. (Geol. Suppl.)* 3, pp. 215–236, pls. 24–26.
- Williams, G.L., Brideaux, W.W., 1975. Palynologic analyses of upper Mesozoic and Cenozoic rocks of the Grand Banks, Atlantic Continental Margin. *Geol. Surv. Can. Bull.* 236, 1–68, pls. 1–47.
- Williams, G.L., Bujak, J.P., 1977. Cenozoic palynostratigraphy of offshore eastern Canada. In: Elisk, W.C. (Ed.), *Contributions of stratigraphic palynology (with emphasis on North America)*. Vol. 1. *Cenozoic palynology*. *Am. Assoc. Stratigr. Palynol. Contrib. Ser.* 5A, pp. 14–47.
- Williams, G.L., Bujak, J.P., 1985. Mesozoic and Cenozoic dinoflagellates. In: Bolli, H.M., Saunders, J.B., Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy*. Cambridge University Press, 847–964.

- Wilson, G.J., 1971. Observations on European Late Cretaceous dinoflagellate cysts. Part 1. In: Farinacci, A. (Ed.), *Proc. 2nd Planktonic Conf. (Rome, 1970)* 2, 1259–1275.
- Wilson, O.J., 1974. Upper Campanian and Maastrichtian dinoflagellate cysts from the Maastricht region and Denmark (unpubl. PhD thesis). University of Nottingham, Nottingham, United Kingdom, p. 601.
- Wilson, G.J., 1988. Paleocene and Eocene dinoflagellate cysts from Waipawa, Hawkes Bay, New Zealand. *N. Z. Geol. Surv. Paleontol. Bull.* 57, 1–96.
- Yans, J., Marandat, B., Masure, W., Serra-Kiel, J., Schnyder, J., Storme, J.-Y., Marivaux, L., Adnet, S., Vianey-Liaud, M., Tabuce, R., 2014. Refined bio- (benthic foraminifera, dinoflagellate cysts) and chemostratigraphy ($\delta^{13}\text{C}_{\text{org}}$) of the earliest Eocene at Albas-Le Clot (Corbières, France): implications for mammalian biochronology in Southern Europe. *Newslett. Stratigr.* 47, 331–353.
- Zalinskaya, E.D., Naidin, D.P., 1985. Palynological characteristics of the upper Maastrichtian deposits of the Crimea. *Mosc. Soc. Nat. Bull., Geol. Ser.* 60, 80–87 (in Russian).
- Zavada, M., 1979. Palynology of some Cretaceous flysch deposits of central Macedonia, Yugoslavia. *Geol. Balc.* 9, 35–46.
- Zhao, Y., Morzadec-Kerfourn, M.T., 2009. Kystes de dinoflagellés et paléoenvironnement quaternaire dans la région Izu-Bonin, nord-ouest Pacifique (ODP leg 125, Site 782A et leg 126, Site 791B). *Quaternaire* 20, 195–213 (in French).
- Zosimovish, V.Y., Knyazkova, I.L., Lyul'yeva, S.A., Plotnikova, L.F., Solyanik, E.A., Strekozov, S.N., Chubar, Z.V., Shevchenko, T.V., Shevchuk, E.A., 2006. New data on the stratigraphy of Upper Cretaceous sediments in the Gruzskoy Yelanchik Basin of the Eastern Azov region. *Collect. Sci. Work. Inst. Geol. Sci. Natl. Acad. Sci. Ukr.* 198–208 (in Ukrainian).

Appendix 3. Supplementary data

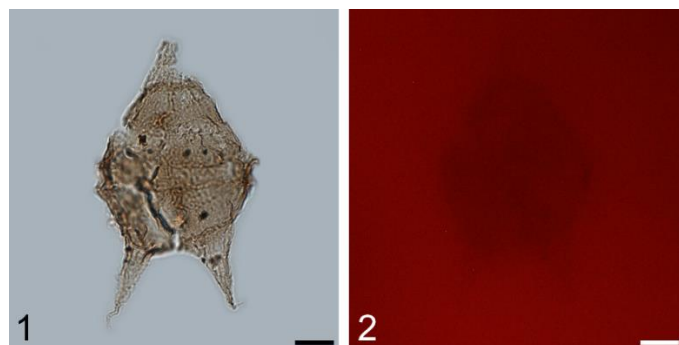
Table 1. *Phelodinium fensomei* sp. nov. specimen counts, concentrations and relative abundance

Sample		Sediment	<i>Lycopodium clavatum</i> spike			Dinoflagellate Cysts	<i>Phelodinium fensomei</i> sp. nov.		
Present Study	UVic ID	Dry Weight (g)	Batch Number	Spores/Tablet	Spore Count	Total Count	Count	Cysts g ⁻¹	% DC
82	19-81	6.027	2013001	27,560	184 (641)	450 (1,568)	0 (3)	21	0.19
77	17-691	10.15	177745	18,584	145 (240)	433 (715)	1 (1)	8	0.14
76	19-77	6.066	177745	18,584	126 (270)	455 (975)	1 (1)	11	0.10
75	17-689	10.17	177745	18,584	76 (205)	435 (1,173)	1 (2)	23	0.17
74	17-690	10.21	177745	18,584	67 (262)	433 (1,693)	1 (1)	7	0.06
67	19-71	6.026	177745	18,584	200 (472)	448 (1,057)	0 (1)	7	0.09
64	19-68	6.050	177745	18,584	71 (233)	464 (1,523)	2 (2)	26	0.13
63	19-67	6.043	177745	18,584	104 (244)	439 (1,030)	1 (1)	13	0.10
62	18-178	4.420	177745	18,584	64 (385)	438 (2,635)	3 (4)	44	0.15

Float samples are highlighted in grey. Bold typeface values are those of counted specimens. Regular typeface values are extrapolated. Bracketed values are those relative to a total dinoflagellate cyst count > 300.

Table 2. *Phelodinium fensomei* sp. nov. specimen measurements (* = holotype).

Sample	UVic ID/slide	EF Coordinates	W	L	L ₁	L ₂	A ₁	A ₂	C	S
82	19-81/A	O40/2	38.7	62.4	30.8	8.3	12	8.5	2.8	9.1
77	17-691/C	F33/2	28.4	—	24.5	—	11.8	—	5.9	13.2
77	17-691/D	T35/1	35.5	67.4	21.5	12.6	12.8	14.9	5.3	14.2
77	17-691/D	C35/1	35.3	68.9	22.6	13.3	14.6	15	3.4	15.2
76	19-77/A	R37/1	—	55.1	14.2	14.2	16.2	11.6	3.9	8.7
75	17-689/C	R45/0	32.4	69.1	22.3	11.8	13.8	17.2	3.9	12.7
75	17-689/C	U47/1	37.9	73.5	20.5	14.4	16.4	17.4	4.7	11.4
75	17-689/E	C39/0	33.4	73.5	25.8	11.5	12.6	18.6	4.9	12.2
74	17-690/C	C38/2	37.7	70.8	16.5	12.7	19.6	16.8	5.1	13.8
74	17-690/C	E43/4	39.3	71.4	25.6	15.3	7.2	18.2	5.1	15
74	17-690/D	K45/1	39.2	—	21.2	15.8	—	22.5	5.6	—
74	17-690/E	G47/1	39.3	76.5	20.5	15	18.3	17.9	4.8	12.8
67	19-71/B	D35/2	36.9	—	18.7	16.2	19.1	—	4.3	11.8
64	19-68/A	A39/3	36.9	65.3	18.4	10.5	—	16.2	4.9	9.9
63	19-67/A	W46/1	33.6	—	15.2	—	—	15	3.5	10.7
62	18-178/A	J32/4	—	81.5	26.1	15.9	16.4	18.1	4.9	—
62	18-178/A	C39/3	35.3	—	23.1	—	18.2	18	4.2	—
62	18-178/A	C41/3	35.7	85.5	23.5	18.6	16.1	21.1	6.1	12.8
62	18-178/A	C43/3	—	—	—	19.1	—	20.3	4.7	—
62	18-178/B	K44/0	38.1	—	21.3	17.8	—	—	6.3	13.6
62	18-178/C	Y33/0	42.4	73	22	10.3	19.7	16.8	4.1	10.3
62	18-178/E	N31/4	32.6	76.2	27.2	14.6	9.3	19.9	5.2	—
62	18-178/F	J31/0	—	—	18.1	11	—	—	4.7	10.9
62	18-178/F*	Q44/1	38.9	84.5	23.7	15.1	16.6	24.1	6.1	11.8
62	19-31/B	C35/0	40.5	83.4	23.6	16.1	17.6	21.1	4.9	9.5
62	19-31/C	S36/1	—	—	—	14.7	—	16.6	5.3	—
62	19-31/C	G41/4	—	78	17.9	15.6	17.4	21.1	5.9	—
	UVic ID/stub									
62	19-31/P		42.9	—	20	17.4	—	23.2	6.2	—



← **Supplementary Figure 1.** *Phelodinium fensomei* sp. nov., Sample 74, 20 m (UVic 17-690, slide D, EF K45/1). 1, light transmitted photomicrograph. 2, epifluorescence photomicrograph. Scale bars = 10 μm.

Appendix 4.A. Calcareous dinoflagellate cyst data | DSDP Site 577, Hole 577, Core 12, Shatsky Rise

Table 1. Calcareous dinoflagellate cyst counts, diversity and concentrations

Sample No.	UVic ID No.	Hole 577 Max Depth (mbsf) ¹	Hole 577 Core 12 Section	Section Sample Interval (cm)	Interval (~cm) relative to K/PG boundary ^{2, 3}	<i>Lycopodium</i> Batch No.	<i>Lycopodium</i> Spores/Tablet	<i>Lycopodium</i> Spores Counted	Dried Sediment Weight (g)	Total Calcareous Dinoflagellate Cysts (CDCs)	Total CDC Concentration (mg ⁻¹)	Shannon-Wiener Index (H)	Shannon Evenness (E)	<i>Cervisiella operculata</i>	<i>Calciodinellum clamosum</i> subsp. <i>clamosum</i>	<i>Thoracosphaera heimii</i> morphotype A	<i>Thoracosphaera heimii</i> morphotype B	<i>Pirumella edgarii</i>	<i>Fuetererella tesserula</i>	<i>Pernambugia tuberosa</i>	<i>Calciodinellum elongatum</i>	Cyst Type A
16	2020-16	110.61	5	10–11	119/120	3862	9,666	89	0.549	209	41	1.32	0.635	33	117	23	24	1		1	1	9
15	2020-15	111.21	5	70–71	59/60	3862	9,666	5	1.3929	206	286	1.578	0.759	52	61	37	45	3	3	3	2	
14	2020-14	111.41	5	90–91	39/40	3862	9,666	16	1.3933	213	92	1.436	0.738	78	63	45	19		2	3	3	
13	2020-13	111.61	5	110–111	19/20	3862	9,666	15	1.1982	208	112	1.442	0.805	75	47	34	47		3		2	
12	2020-12	111.65	5	114–115	15/16	3862	9,666	36	1.4068	215	41	1.439	0.74	81	47	52	28	3		1	2	
11	2020-11	111.69	5	118–119	11/12	3862	9,666	15	1.3605	213	101	1.492	0.717	98	27	41	33	3	4	5	2	
10	2020-10	111.73	5	122–123	7/8	3862	9,666	14	1.3818	219	109	1.493	0.68	78	31	69	31	1	2	4	2	1
9	2020-9	111.77	5	126–127	3/4	3862	9,666	16	1.7612	217	74	1.454	0.747	81	46	57	25	1	4	3		
8	2020-8	111.85	5	134–135	–3/–4	3862	9,666	37	1.5029	215	37	1.494	0.68	93	37	49	24	1	2	3	3	3
7	2020-7	111.89	5	138–139	–7/–8	3862	9,666	101	1.6319	213	12	1.423	0.731	81	60	48	13	8		2	1	
6	2020-6	111.93	5	142–143	–11/–12	3862	9,666	34	1.1893	212	51	1.514	0.728	54	45	74	30	3	2	2	2	
5	2020-5	111.97	5	146–147	–15/–16	3862	9,666	70	1.1076	205	26	1.429	0.734	39	65	75	17	6		2		1
4	2020-4	111.99	5	148–149	–19/–20	3862	9,666	169	1.1893	206	10	1.566	0.713	42	65	56	32	4	1	2	3	1
3	2020-3	112.21	6	20–21	–39/–40	3862	9,666	138	1.2531	206	12	1.468	0.706	39	75	57	28	2	1	3	1	
2	2020-2	112.41	6	40–41	–59/–60	3862	9,666	35	1.6274	206	35	1.342	0.689	55	91	36	20	1	1	2		
1	2020-1	113.02	6	101–102	–119/–120	3862	9,666	116	0.0359	211	490	1.519	0.781	45	70	51	35		2	1		7
														min	33	27	23	13	1	1	1	1
														max	98	117	75	47	8	4	5	3
														av	64	59	50	28	3	2	2	4

¹Dickens, G.R., Backman, J., 2013. Core alignment and composite depth scale for the lower Paleogene through uppermost Cretaceous interval at Deep Sea Drilling Project Site 577. *Newsletters in Stratigraphy* 46, 47–68.

²Monechi, S., 1985. Campanian to Pleistocene calcareous nannofossil stratigraphy from northwest Pacific Ocean, Deep Sea Drilling Project Leg 86. *Deep Sea Drilling Project, Initial Reports* 86, 301–336.

³Monechi, S., Bleil, U., Backman, J., 1985. Magnetobiochronology of Late Cretaceous–Paleogene and Late Cenozoic pelagic sedimentary sequences from the northwest Pacific (Deep Sea Drilling Project, Leg 86, Site 577). *Deep Sea Drilling Project, Initial Reports* 86, 787–797.

Table 2. Calcareous dinoflagellate cyst relative abundances

Sample No.	UVic ID No.	Hole 577 Max Depth (mbsf) ¹	Hole 577 Section	Section Sample Interval (cm)	Interval (~cm) relative to K/PG boundary ^{2,3}	<i>Lycopodium</i> Batch No.	<i>Lycopodium</i> Spores/Tablet	<i>Lycopodium</i> Spores Counted	Dried Sediment Weight (g)	Total Calcareous Dinoflagellate Cysts (CDCs)	<i>Cervisiella operculata</i>	<i>Calciodinellum clamosum</i> subsp. <i>clamosum</i>	<i>Thoracosphaera heimii</i> morphotype A	<i>Thoracosphaera heimii</i> morphotype B	<i>Pirumella edgarii</i>	<i>Fuetterella tesserula</i>	<i>Pernambugia tuberosa</i>	<i>Calciodinellum elongatum</i>	Cyst Type A
16	20-16	110.61	5	10–11	119/120	3862	9,666	89	0.549	209	15.8	56.0	11.0	11.5	0.5		0.5	0.5	4.3
15	20-15	111.21	5	70–71	59/60	3862	9,666	5	1.3929	206	25.2	29.6	18.0	21.8	1.5	1.5	1.5	1.0	
14	20-14	111.41	5	90–91	39/40	3862	9,666	16	1.3933	213	36.6	29.6	21.1	8.9		0.9	1.4	1.4	
13	20-13	111.61	5	110–111	19/20	3862	9,666	15	1.1982	208	36.1	22.6	16.3	22.6		1.4		1.0	
12	20-12	111.65	5	114–115	15/16	3862	9,666	36	1.4068	215	37.7	21.9	24.2	13.0	1.4		0.5	0.9	
11	20-11	111.69	5	118–119	11/12	3862	9,666	15	1.3605	213	46.0	12.7	19.2	15.5	1.4	1.9	2.3	0.9	
10	20-10	111.73	5	122–123	7/8	3862	9,666	14	1.3818	219	35.6	14.2	31.5	14.2	0.5	0.9	1.8	0.9	0.5
9	20-9	111.77	5	126–127	3/4	3862	9,666	16	1.7612	217	37.3	21.2	26.3	11.5	0.5	1.8	1.4		
8	20-8	111.85	5	134–135	–3/–4	3862	9,666	37	1.5029	215	43.3	17.2	22.8	11.2	0.5	0.9	1.4	1.4	1.4
7	20-7	111.89	5	138–139	–7/–8	3862	9,666	101	1.6319	213	38.0	28.2	22.5	6.1	3.8		0.9	0.5	
6	20-6	111.93	5	142–143	–11/–12	3862	9,666	34	1.1893	212	25.5	21.2	34.9	14.2	1.4	0.9	0.9	0.9	
5	20-5	111.97	5	146–147	–15/–16	3862	9,666	70	1.1076	205	19.0	31.7	36.6	8.3	2.9		1.0		0.5
4	20-4	111.99	5	148–149	–19/–20	3862	9,666	169	1.1893	206	20.4	31.6	27.2	15.5	1.9	0.5	1.0	1.5	0.5
3	20-3	112.21	6	20–21	–39/–40	3862	9,666	138	1.2531	206	18.9	36.4	27.7	13.6	1.0	0.5	1.5	0.5	
2	20-2	112.41	6	40–41	–59/–60	3862	9,666	35	1.6274	206	26.7	44.2	17.5	9.7	0.5	0.5	1.0		
1	20-1	113.02	6	101–102	–119/–120	3862	9,666	116	0.0359	211	21.3	33.2	24.2	16.6		0.9	0.5		3.3
											min	15.8	12.7	11.0	6.1	0	0	0	0
											max	46.0	56.0	36.6	22.6	3.8	1.9	2.3	1.5
											av	30.2	28.2	23.8	13.4	1.1	0.8	1.1	0.7

Appendix 4.B. Measurements of *Thoracosphaera heimii* (Kamptner, 1927) Fütterer, 1976
| DSDP Site 577, Hole 577, Core 12, Shatsky Rise

Table 1. Specimens of *Thoracosphaera heimii* morphotype A

Sample	UVic ID/Slide	EF Coordinates	Figures	Measurements (µm)			
				Diameter (D)	Wall Thickness (Wt)	Wt/Td	Archeopyle Width
2	2020-2/A	U47/2		25.9	2.6	0.100	8.1
2	2020-2/A	Y32/0		20	3.4	0.170	4.7
2	2020-2/A	Q28/4		21	2.3	0.110	6.8
2	2020-2/A	Q38/0		23.7	4	0.169	–
2	2020-2/A	P38/2		23.9	2.3	0.096	7.7
3	2020-3/B	J34/0	Plate 4, Figs. 1–3	34.7	4.2	0.121	13.4
3	2020-3/B	F37/4	Plate 4, Figs. 4–6	29	3.7	0.128	9.6
3	2020-3/B	N33/1		23	2.6	0.113	–
3	2020-3/B	N32/0		29.4	4.4	0.150	9.4
3	2020-3/B	N27/0		25.8	3.3	0.128	8.4
3	2020-3/B	O/41/4		20.1	2	0.100	–
3	2020-3/B	O44/1		33	4	0.121	–
3	2020-3/B	O34/4		24.1	2.3	0.095	–
3	2020-3/B	P44/0		23.5	3.9	0.166	–
3	2020-3/B	P31/2		28.5	4	0.140	8.9
3	2020-3/B	R32/1		28.6	3.4	0.119	9.9
3	2020-3/B	R31/0		20.2	2.1	0.104	8.8
5	2020-5/A	K24/0		24.7	2.2	0.089	9.7
5	2020-5/A	H33/0		20	2.6	0.130	7.5
5	2020-5/A	H44/3		22.8	2.2	0.096	6.1
5	2020-5/A	J44/4		32.6	2.3	0.071	13.3
5	2020-5/A	K46/0		25	3.2	0.128	7.5
5	2020-5/A	L46/0		30.8	3.9	0.127	14
9	2020-5/A	O42/2		29.5	3.7	0.125	10.8
9	2020-9/A	C33/1	Plate 4, Figs. 7, 8	25.3	2.8	0.111	9.9
9	2020-9/A	F32/3		33.4	3.7	0.111	13.2
9	2020-9/A	E42/1		27.2	2.9	0.107	12.6
9	2020-9/A	G43/1		23.6	2.4	0.102	–
9	2020-9/A	E25/0		28.6	3.3	0.115	9.1
9	2020-9/A	G35/1		29.3	2.4	0.082	10.5
9	2020-9/A	G32/4		29.4	2.8	0.095	12.8
9	2020-9/A	J32/0		21.7	3.5	0.161	7.8
13	2020-13/A	Q35/0		31	3.4	0.110	10
13	2020-13/A	R28/2		25.5	3.1	0.122	9.4
13	2020-13/A	H40/0		28.2	2.8	0.099	8.9
13	2020-13/A	H42/2		27.9	2.8	0.100	8.3
13	2020-13/A	J30/1		23.3	2.7	0.116	8.7
13	2020-13/A	Q27/0		22.6	2.1	0.093	9
13	2020-13/A	K30/2		26.3	2.9	0.110	–

Table 2. Specimens of *Thoracosphaera heimii* morphotype B

Sample	UVic ID/Slide	EF Coordinates	Figures	Measurements (μm)			
				Diameter (D)	Wall Thickness (Wt)	Wt/Td	Archeopyle Width
2	2020-2/A	U36/4		17.1	1.3	0.076	6.4
2	2020-2/A	Q35/3		16.6	1.2	0.072	6.5
2	2020-2/A	Q38/3		21.3	1.6	0.075	6.9
2	2020-2/A	F47/2		16.4	1.3	0.079	5.1
2	2020-2/A	Q35/1		19.1	1.1	0.058	4.4
2	2020-2/A	J51/0		18.8	1.1	0.059	7.5
2	2020-2/A	J33/0		19.5	1.2	0.062	—
2	2020-2/A	K36/1		17.5	1	0.057	5.9
3	2020-3/B	N29/1		19.1	1.4	0.073	—
3	2020-3/B	O35/2		21.1	1.6	0.076	—
3	2020-3/B	O32/0		20.7	1.7	0.082	6.4
3	2020-3/B	O25/1		17.9	1.7	0.095	5.3
3	2020-3/B	Q39/0		19.5	1.6	0.082	5.9
3	2020-3/B	Q25/0		18.2	1.2	0.066	—
5	2020-5/A	J27/0	Plate 5, Figs. 1–3	18.2	1.5	0.082	5.4
5	2020-5/A	M23/0	Plate 5, Figs. 4–6	17	1.6	0.094	6.6
5	2020-5/A	G32/4		21.5	1.8	0.084	7
5	2020-5/A	N41/3	Plate 5, Figs. 7–9	23.5	1.6	0.068	—
5	2020-5/A	G40/0		18.4	1.5	0.082	—
5	2020-5/A	J40/3		17.4	1.5	0.086	—
5	2020-5/A	L45/2		19.3	1.3	0.067	6.4
5	2020-5/A	L36/4		20.2	1.6	0.079	7.1
5	2020-5/A	Q36/4		20.1	1.2	0.060	7.1
5	2020-5/A	R34/1		16.6	1.6	0.096	6.4
9	2020-5/A	E37/2		19.1	1.2	0.063	6.9
9	2020-5/A	R37/0		20.4	1.2	0.059	—
9	2020-5/A	G39/0		21.3	1.5	0.070	8
9	2020-5/A	H25/0		19.6	1.1	0.056	8.9
9	2020-5/A	K35/2		17.9	1.7	0.095	6.2
9	2020-5/A	J27/0		21.8	1.2	0.055	7.6
9	2020-5/A	M24/2		19.8	1.5	0.076	6.2
13	2020-13/A	H48/1		19.1	1.3	0.068	8.2
13	2020-13/A	G39/4		20.3	1.3	0.064	8.3
13	2020-13/A	H32/1		17.9	1.2	0.067	7.5
13	2020-13/A	H36/0		20.6	1.3	0.063	7.3
13	2020-13/A	H46/4		18.4	1	0.054	6.1
13	2020-13/A	J31/0		17.5	0.9	0.051	—
13	2020-13/A	J38/0		20.7	1.5	0.072	7.5
13	2020-13/A	K24/1		17.8	1.5	0.084	—